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A Re-calculation of Rowland's value for the Mechanical Equivalent of Heat in terms of the Paris Hydrogen Thermometer.

1 Design and Construction of new apparatus for testing and comparing thermometers.

2. Comparison of Rowland's three thermometers with three Tonnelot thermometers.

Dissertation
Submitted to the Board of University Studies
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Doctor of Philosophy,
by
William Scofield Day.
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The author wishes to express his appreciation of Professor Rowland's kindness in allowing the use of his thermometers for the purpose of these comparisons, and his obligation to both Professor Rowland and Professor Ames for their frequent aid and advice in the course of the work.

Although the general plan of the apparatus described here is the author's, he wishes to express his deep sense of obligation to Mr. W.T.Mather, Fellow of the Johns Hopkins University, for his aid at almost every step in the mechanical details of its design and construction.

1. Introduction. Object of Comparison, etc.

The Mechanical Equivalent of Heat, in the C.G.S. system is the value of J in the equation

$$J = \frac{dW}{dt^\circ}$$

where dW is the number of ergs required, when expended in heat, to raise the temperature of one gram of water dt° C. on the absolute scale. This quantity, $\frac{dW}{dt}$, differs at different temperatures on account of the variation of the specific heat of water.

Rowland's measurement of the Mechanical Equivalent in 1877-78, (Proc. American Acad. of Arts and Sciences, 15. p. 75, 1879,) still remains as probably the best one in which the heat is produced by the expenditure of mechanical energy. Within the last few years, however, a number of other determinations have been made, in which the heat is produced by the expenditure of electrical energy, and these have given values differing a little from Rowland's. Schuster and Gannon (Phil. Trans. 186 A. p. 458, 1895), give the following comparative values. The unit is foot-pounds at Greenwich, ($g = 981.17$ cm/sec^2), and the temperature scale is that of the Paris nitrogen thermometer.

	Joule.	Rowland.	Griffiths.	Schuster & G.
At 19.1° C.	774	776.1	779.1	778.5
At 15° C.	775	778.3	780.2	779.7

In the experiments of Joule and Rowland the heat was produced

by mechanical stirring, in those of Griffiths, and of Schuster, the heat was produced electrically. Judging from these four experiments, the electrical methods seem to give higher results than the mechanical.

The value of $\frac{dW'}{dt°}$ depends not only on the measurement of the quantity dW, but also on the scale of temperature used in measuring dt°. In Rowland's experiments this quantity was measured on the absolute scale, as determined by comparison with an air-thermometer. In view, however, of later and more refined experiments with mercurial and gas-thermometers by various observers, particularly at the International Bureau of Weights and Measures, at Sèvres, near Paris, the present writer determined to make some experiments on the specific heat of water. At the suggestion of Professor Rowland, however, it was decided to be more important to make a careful comparison of his thermometers with the Paris hydrogen thermometer. This was the object of the investigation here described. For this purpose there were secured three Tonnelot thermometers which had been studied at the International Bureau, and compared with their standards at several points of the scale. These three were compared with three of Rowland's thermometers, used in his mechanical equivalent experiment. The corrections to the value of the mechanical equivalent found in this way were rather small. The general result is contained in Table 17, on page 93. It is also represented by the curves on page 4[illegible].

2. Thermometers used. Dimensions and constants.

Rowland's value of the mechanical equivalent is the result of fourteen experiments, made with four different thermometers in the calorimeter. In thirteen of these he used three thermometers made by Baudin in 1876 - 77, and in one he used a thermometer made by Welsh in 1853, and called, in Rowland's paper, the Kew standard. This thermometer belonged to the University of Pennsylvania, and was not available for this comparison. The three Baudin thermometers were numbered 6163, 6165, and 6166. Of these, 6163 was used in eight experiments, 6165 in one experiment, and 6166 in four experiments. 6166 was also compared by Joule with one of his own thermometers. (Rowland, Proc. Am. Acad., 16, p. 38, 1880.)

The three Tonnelot thermometers were numbered 11800, 11801, and 11811, and were made between November 1895, and January, 1896. A complete study of these was made by the International Bureau, including a comparison at several points with the standards of the Bureau, which had previously been compared with the hydrogen thermometer. After this study had been made, two of them, Nos. 11800, and 11811, were unfortunately broken in transportation to Baltimore. They were however, repaired by the maker, and at no additional expense, through the kindness, which seems habitual, of the

Bureau, and of M. Guillaume, a completely new study of them, including comparisons, was made. The dimensions and principal constants of these thermometers and of Rowland's Baudin thermometers, are contained in the following table.

TABLE 1.

Tonnelot	11800	11801	11811
Middle of bulb to zero of scale.	55.8 mm.	59 mm.	74.3 mm.
Length of a degree.	5.86 mm.	5.853 mm.	3.91 mm.
Length of bulb.	48 mm	50, mm.	50, mm
Total length.	701 mm.	704. mm.	679. mm.
Value in degrees of one division.	0.870604	1°.000014	0°.977160
Coefficient of exterior pressure	0.0001439	.0001159	.0001409
Coefficient of interior pressure.	0.0001593	.0001313	.0001563
Extreme divisions of scale			

Baudin	6163	6165	6166
Middle of bulb to zero of scale.	34 mm.	37 mm.	34 mm.
Length of a numbered division.	1 cm.	1 cm.	1 cm.
Total length.	501 mm.	500 mm.	497 mm.
Value in degrees of one centimeter.	1.114	0.8470	0.779
Coefficient of exterior pressure.	0.000247	0.000347	0.000411
Coefficient of interior pressure.	0.000261	0.000366	0.000431
Extreme divisions of scale.	0-42.5	0--42.0	o--42.
Diameter of stem.	4.5 mm	4.3 mm	4.3 mm

Below, in Table 2, p.54, is given the results of the comparisons of the three Tonnelot thermometers with the standards of the Bureau. Each reading is the average of a good many observations at neighboring temperatures. The column headed "mean temperature" gives the temperature on the scale of the hard glass thermometers. The second column gives the corresponding reading of the Tonnelot thermometer. M means the temperature on the mean scale of the hard glass thermometers. These departures from the hard glass scale are corrections which must be added with their sign changed to the indications of the thermometer to which they relate.

In the case of Tonnelot 11800, after it was repaired, it no longer read as high as 100°, and the fundamental interval could not be determined in the usual way. The value of a degree was therefore determined by comparisons with the standards at three different points, and from these observations the mean value of a degree was calculated. The table given for this thermometer shows the departure of its indications, when the value of a degree is calculated in this way, from the standards of the Bureau. In this case, owing to the way in which the departure has been calculated, it is to be considered as a correction which must be added with the same sign, to the indications of the thermometer 11800.

At the end of this paper there is given, for the sake of completeness, a table for the Tonnelot thermometers, showing the calibration corrections at the principal points, as given in the certificate of the Bureau. These corrections were determined directly by the calibration, the corrections for the intervening points being determined from them by some method of interpolation. Table 18 p.94.

The Tonnelot thermometers were made of French "verre dur" with transparent stems, and were divided to tenths of a degree. The Baudin thermometers were divided into millimeters, and the centimeters, which corresponded in a rough way to degrees, were numbered.

3. Manner in which Rowland used his thermometers.

In comparing these various thermometers, it was necessary to use them in the way in which they were originally used when they were standardized. The Tonnelot thermometers had to be used in the manner described by Guillaume in his "Thermométrie de Précision," and in the printed notice that came from the Bureau with the thermometer certificates. Rowland's thermometers were not used in the same way when they were originally compared with the air thermometer. The chief points of difference are in the corrections for internal and external pressure, and in the manner of taking and using the zero point. The present method, as used at the International Bureau, is to determine the pressure coefficients so that any variation in the external

pressure from the standard 760 mm., and any variation in the position of the thermometers from the horizontal, can be corrected for. As to the zero point, this is always calculated from the zero determined immediately after each reading of temperature. Rowland's method, which was the usual one at that time, was to consider the vertical position of the thermometers as the normal one, and to make corrections for changes of external pressure only when they were quite large, as when the thermometer bulb was immersed 60 cm. in the comparison tank. The zero point was also always determined just before a series of readings. It would have been most natural, therefore, to have compared the Tonnelot and Baudin thermometers in a vertical position, applying to the Tonnelot thermometers the proper pressure correction. But there were several difficulties and inconveniences in the way of this. The chief one was the difficulty of constructing a comparison tank such that the Tonnelot thermometers could be quickly and easily removed for the purpose of reading their zeros. Another difficulty was in reading the thermometers. Rowland's original comparisons and use of his thermometers were all made by naked eye observations. Possibly this method is accurate enough where the thermometers are used in the old way, as even with considerable care there are apt to be irregularities due to the uncertain position of the zero. But to read the thermometers accurately, it seemed to be necessary to use a telescope and micrometer. This could be applied so much more conveniently to a horizontal tank than to a vertical one, that this, together

with the necessity for frequent removals mentioned above, made the writer decide to use a horizontal tank. This made it necessary to measure the interior pressure coefficient of the Baudin thermometers, but the measurement could be made with great accuracy. In either case, a pressure correction would have to be applied to one set of thermometers, either to the Baudin thermometers used horizontally, or the Tonnelot thermometers used vertically.

4. Manner in which Tonnelot thermometers are standardized and used.

It may be well to explain here briefly how thermometers are studied and used at the International Bureau.

The uniformity of the graduation is first investigated by means of a dividing engine, and if it is not sufficiently correct the thermometer is rejected. Next a calibration is made. This determines the corrections to be applied to certain "principal points" of the scale, generally two degrees apart, in order to make the readings of the thermometer after the correction has been applied, what they would have been if the tube had been of perfectly uniform bore. These corrections are generally calculated on the system 0°-100°, that is, so that the corrections at the points 0° and 100° are zero. Next the external pressure coefficient is determined by subjecting the thermometer to known variations of pressure, and measuring the corresponding changes in the reading. This pressure coefficient generally

gives the number of degrees the reading of the thermometer is changed by a change in the external pressure of 1 mm. of mercury. From this the interior pressure coefficient is calculated by adding the quantity $\overset{\circ}{0}$.000 015 4. This quantity depends on the difference in the compressibility of mercury and of glass, and is the value for French hard glass. It is generally a small fraction, 10% or less, of the whole pressure coefficient. It differs of course somewhat for different kinds of glass, but this difference is a still smaller fraction of the whole pressure coefficient. These two coefficients are generally denoted by the letters β_e and β_i respectively.

The next constant determined is the fundamental interval, or the number of degrees i.e., scale divisions between the 0° and the 100° point. This gives the value of the degree or scale division on the Centigrade scale. From all these data the temperature on the scale of this particular thermometer can be determined. When such a thermometer is compared with others of the same kind of glass, it will, in general, agree very closely. The small residual differences which are found may be due to some small errors in the calibration, or to a small departure of that particular piece of glass from the law of expansion of the other thermometers. This departure, in the case of the Tonnelot thermometers used in this comparison, is the difference given in Table 2. p. 54. A number of thermometers whose mean reading represents the hard glass scale have been compared with the hydrogen therm-

ometer, and the differences noted. Thus in the use of a hard glass thermometer we have a means of measuring temperatures on the hydrogen scale.

Rowland's thermometers were originally compared in quite a different way. They were calibrated of course, and the relative volumes of different parts of the tube were found. The apparent volume of mercury in glass, when the thermometer is in an upright position, was assumed to be a function of the second degree of the temperature on the air thermometer. This volume was measured from a constant zero, that is, a zero point taken at the beginning of a series of readings. The thermometer, when not in use, remained at a temperature of from 18° to 20° C. Just before making a comparison it was placed in ice, and allowed to remain there for an hour or two. Then the position of the zero was read, and this zero was used from which to estimate the subsequent readings. Having made a number of comparisons with the air thermometer, the values of the constants in the formula of the second degree were determined by the method of least squares. From the formula, then, the temperature on the air thermometer corresponding to each centimeter of the scale, could be calculated. In this way Rowland constructed a table for each of the Baudin thermometers. These tables are given on pp. 115-116 of his paper on the mechanical equivalent. They are reproduced here for convenience, in Table 3. p.55 The corrections to reduce to the air thermometer are deduced from the experiments of Thomson and Joule. They are given here

as Rowland gives them on page 114 of his paper. (Table 4. p 57) In Rowland's use of the thermometers, no correction is made for internal pressure, as they are always supposed to be used vertically. No correction is made for external pressure, except in the case of the comparisons made in the comparison tank, in which the bulbs were from 60 to 70 cm. below the surface of the water.

5. Description of Instruments employed, and manner of using them.

In carrying out these comparisons, it was found necessary to construct several pieces of apparatus. As some of these differed a little from any that had been used before, it will be convenient to give a short description of them here.

a. Pressure apparatus.

The pressure coefficients were determined in a manner practically identical with that described by Guillaume in his "Thermometrie de Precision", p. 104. The apparatus used is represented by the diagram, Fig. 1. p. 101. It consisted of a vertical glass tube about 1.5 cm. in diameter, in which the thermometer could be hung. Matters were so arranged by means of brass three-way tubes and stop-cocks that this tube could be connected alternately with an exhausted bottle, and then with the open air, so that the pressure could be varied from 76 cm.

to 5 or 6 cm. Connected with the glass tube in which the thermometer hung was a mercury manometer by which the change in pressure could be measured. The lower end of the tube containing the thermometer was filled with mercury so as to be a better heat-conductor. The tube itself dipped into a vessel of water. This vessel was wrapped with cotton wool, and a little oil was placed on the surface of the water to prevent the irregular loss of heat due to evaporation. The method of making the measurements will be described in section 6, p. 24.

b. Micrometer telescope..

The thermometers were always read with a micrometer telescope. The only objection to this is that in some cases it takes so much time that it is not possible to keep the thermometer at a constant temperature long enough. So far as the zero points were concerned, there was not much trouble in these comparisons, as the highest temperatures measured were not above 40°, and the recovery of the zero did not seem to be sufficiently rapid, after an exposure to this temperature, to prevent micrometer readings. In the case of the actual comparisons, the tank was so constructed that here also the temperature remained constant long enough to make observations with a micrometer. The reading telescope used was made by Bausch and Lomb, and resembled outwardly a microscope tube. The object glass had a focal length of 7.5 cm., and it was used at a distance from the thermometers of about 18 cm. The micrometer was not an eye-piece micrometer, as it

would not have been possible to avoid parallax in a telescope used so near to the object as this. The whole telescope was made to move in ways when the micrometer screw was turned. In the field of view, in front of the eye-piece, were two spider lines, arranged to cross at the same angle as an X. The micrometer screw had a pitch of 0.5 mm. and the head was graduated to 0.01 mm. and by estimation of tenths, it could be read to 0.001 mm. It was made by L.S. Starrett, of Athol, Mass., and was simply an adaptation of one of his screw micrometers. Besides its cheapness due to the fact of its being a commercial instrument, it could be moved with great rapidity by means of the small spindle on the end. The micrometer telescope is shown in Fig.2. p.103. When the telescope was used to read the zero points and measure the pressure coefficients, it was placed on a frame consisting of two upright steel bars, 1.27 cm. in diameter, and 6.3 cm apart. These were fastened to a heavy iron base. See Fig.2. p.103. It formed a sort of cathetometer. The telescope was constructed so that it could be quickly removed and placed on the ways of the comparison tank. When reading the thermometers in the "zero tank", they were made vertical by means of a plumb line, and the telescope was made horizontal by means of a level. When this adjustment had been made, no appreciable difference could be observed between observations made with the divisions in front and those with the divisions behind the tube. When readings were taken in the comparison tank, ~~it~~ this was first adjusted by means of a level so that the thermometer stems were

horizontal, and then the telescope was adjusted by means of a level so that its axis was vertical.

c. Comparison tank.

The comparison tank was devised to fulfil the following requirements.

1. The thermometers must be easily removed for the purpose of taking zeros.

2. They must remain at a practically constant temperature for four or five minutes.

3. They must be easily and quickly read by means of a micrometer telescope sliding on ways above the tank.

4. The supports on which the thermometers rest must be so solid and firmly fastened to the ways on which the telescope slides, that there will be no possibility of any accidental relative motion of the telescope and the thermometer.

To fulfil the first requirement, it was decided to have a horizontal tank as explained at the beginning of this paper. (p.9) The tank was made of sheet copper in the form of a rectangular box, 92 cm. long, 21 cm. wide, and 23 cm. deep. A section of it is represented in Fig. 3, p.105. The top was composed of a movable lid, made of a brass casting. This lid had a flange that was planed on the under side so as to fit a planed brass rim forming the top of the sides of the tank. A piece of sheet india-rubber formed a packing between the two parts to pre-

vent the escape of water. After the lid had been placed in position, it could be screwed down tightly by means of a number of C-clamps placed around the side. The lid was made in the form of a frame holding a piece of plate glass, forming a window through which the thermometers could be read. As shown in Fig. 3 , this window was not much more than 1.5 cm. from the stems of the thermometers.

In order to fulfil the second requirement, the tank was placed inside of a larger wooden box whose walls were everywhere about 5 cm. from the sides of the tank, and the intervening space was filled with cotton wool. This protected the tank very well, except at the top, from too rapid a loss or gain of heat from the air, when it was at a different temperature from that of the room. The layer of cotton did not extend quite up to the top of the tank. The non-conducting layer above this point had to be easily removable to allow the removal of the cover of the tank. A covering of felt, about two centimenters thick was constructed. This extended over all the parts of the tank not protected by the cotton, except the glass window. This had to be exposed to allow of reading the thermometers, but if it had been necessary, the greater part of this might have been covered also.
In order still further to protect the thermometers from any change of temperature, the bulbs were placed inside ~~of~~ a brass box, shown in Fig. 3 in the tank, and in Fig. p.105, in more detail. This box was 10.5 cm. long, 8 cm. wide, and 5 cm. deep It was so constructed that two lids on the top, and two on the

bottom could be opened or closed from the outside of the tank. While the water was being stirred, in the manner to be described presently, this box was kept open. As soon as the water had attained to a uniform temperature, and everything was ready to make a comparison, the stirring was stopped, and the lids of the box were closed. The bulbs were thus shut off completely from any convection currents. In this manner the thermometers could be kept at a constant temperature for a considerable time.

The water was stirred by three paddle-wheels, operated from the outside of the box by a crank. They are represented in Fig. 3 p. 105. One of the paddle wheels was immediately under the box containing the bulbs.

In order to heat the water in the tank to bring it to any desired temperature, a brass tube ran along it from end to end near the bottom. This did not communicate with the water of the tank, but opened into the air at each end. Steam was passed into it until the water reached the temperature desired.

Fastened to the lid of the tank were upright brass posts which held the ways on which the micrometer telescope ran. The telescope had freedom to move in two horizontal directions at right angles to each other, so that it could be placed quickly over any part of the tank, and used to read any thermometer at any part of its scale. The thermometers rested on little brass beams which were fastened to the brass rim of the tank. As this rim was clamped securely to the brass lid which carried the ways, the fourth requirement was secured.

When the tank was full and the lid on, the thermometer bulbs were about 5.7 cm. below the surface of the water.

d. Zero tank.

In taking the zero points of thermometers in the ordinary tank, it is necessary to plunge the thermometer down into the ice until the zero division is a good deal below the surface, so as to make sure that the stem is all at the temperature of 0°C.

(continued on next page.)

When a reading is made, the thermometer is raised until the zero point is just visible. When this is done, not only is the stem apt to become covered with water in films and drops, which make it difficult to read the position of the mercury thread, but it is also apt to become covered with dew, when the laboratory room, as is usual in this country, is at a temperature of from 16° to 20° C. When the zero point is near the bulb, there is also, it seems probable, some danger that a little warmer water may trickle down the stem of the thermometer, and find its way to the bulb in sufficient quantity to make a difference of several thousandths of a degree. In order to do away with these difficulties, it was decided to have the stem practically immersed in the ice for some distance above the zero point, and to read the zero through a tube which should reach from the side of the tank to the part of the stem where the zero point actually was. A device was therefore made use of which is represented in Fig. 4 p. 107. The ice was contained in a cylindrical copper tank, lined with tin, 35.5 cm. high, and 15.2 cm. in diameter. At the bottom there was an opening through which the excess of water could be drawn off. At a distance of 7 cm. from the top of the tank, two openings were made at opposite ends of a diameter, about 2 cm. in diameter. To these there was fitted in a manner that it is not necessary to describe, but so that it could be readily detached, a tube of hard rubber or ebonite, 2 cm. in inside diameter. This ebonite tube extended horizontally across the tank from one side to the other, except that at the

center of it there was a little brass piece that held a sort of drum, with drum-heads of pure sheet rubber. These were perforated with small circular holes in the center, and a thermometer could be inserted perpendicularly through them both. When in position the whole tank could be filled with water and ice, and very little if any water escaped through the joints. As represented in the drawing, the two rubber diaphragms, or drum-heads, were 3.7 cm. apart, and a portion of the stem of that length was therefore not exposed to the ice. This portion of the stem however, must have been nearer in temperature, to 0° C. than ±0.1° C. because when the bulb of a small thermometer, which could detect a difference of 0.1° C. was placed in the air in the center of this ebonite tube, and left there a short time, it indicated a temperature of 0° C. within less than 0°.1 C. There was also no dew deposited on the stem, unless there happened to be a draught of air blowing through the room, as happened in one or two cases.

In using the tank, the ice was broken up into very fine pieces by means of a wooden mallet in a zinc-lined wooden box, and transferred by a tin scoop to the zero tank. Ordinary distilled water was poured on it and it was packed down closely. Before the thermometer was inserted, a glass rod was used to make a hole in the ice to receive it. The thermometer was then placed in position, and the rest of the tank was filled with ice. The actual zero point was generally observed about in the middle of the tube. The water in the ice was also generally

kept at about the same height. The actual height of the water was measured by means of a vertical glass tube placed alongside the tank, and communicating with the outlet tube at the bottom. A brass frame was fastened to the tank, as represented in the drawing, to support the thermometer. A plumb-line served to adjust it vertically. The zero tank had three legs screwed to a wooden base. This base was provided with three thumb-screws which could be adjusted so that the thermometer was vertical, as indicated by the plumb-line.

The ice used was made artificially out of filtered Baltimore city-water, by the Diamond Ice Co. It was frozen by the ammonia process in long and deep, but narrow tanks, with flat sides. The freezing proceeded from the flat sides towards the center, and the ice formed in this way is very pure and clear. Most of the impurities in the water remain in the unfrozen water in the center of the tank. Before all the water is frozen, the process is stopped, and the dirty water drawn off. In order to get some idea of the purity of this ice, Dr. H.C. Jones of the Johns Hopkins University very kindly measured for me, in round numbers, the specific conductivity of the water melted from it, and at the same time, for comparison, the conductivity of ordinary tap-water,-the kind from which the ice had been made,- of ordinary distilled water, and of some water that had been been distilled with special precautions in a block tin condenser, etc. Below is given a table, (Table 5), p.23. showing in round numbers, the specific conductivity, the

dilution, and the corresponding depression of the freezing point, assuming that the impurity is sodium chloride, and also on the assumption that it is ammonium hydroxide. The notation used is that of Ostwald's Allgemeine Chemie, vol. 2 part 1, Chap. 5, p. 621. The constants were also obtained from this chapter. The notation is

μ_v = molecular conductivity, at dilution v. $= kv$

k = specific conductivity. $= \frac{\mu_v}{v}$

v = dilution, that is the number of liters to a gram-molecule. $= \frac{\mu_v}{k}$

3.7°C = depression of the freezing point, supposing the case of a binary electrolyte, and complete dissociation, at a dilution of 1 gram-molecule per liter.

Δ = depression of the freezing point at the dilutions calculated, for the substances assumed.

Table 5.

		NaCl		NH_4OH	
	k	V	Δ	v	Δ
Tap-water.	.110	[illegible]	[illegible]	[illegible]	[illegible]
Ice water.	.016	[illegible]	[illegible]	[illegible]	[illegible]
Ordinary distilled water.	.005	[illegible]	[illegible]	[illegible]	[illegible]
Special distilled water.	.002	[illegible]	[illegible]	[illegible]	[illegible]

Of course these numbers must be considered as only rough approximations, but they give a good idea of the purity of the ice used, and that the error caused by impure ice was a little too small to affect the measurements made. The water from the melted ice was tested for ammonia, and only a trace

was found, so it is probable that the impurity in the water causing the conductivity was not ammonia.

6. Pressure Coefficients.

a. Exterior pressure coefficient.

In measuring the exterior pressure coefficient with the apparatus described on p.13 , the water in the vessel around the tube containing the thermometer was taken several degrees colder than the air of the room. This caused a gradual rise of temperature of the thermometer, and prevented errors due to a falling meniscus. The thermometers in this case also were read with the micrometer telescope, as the rise of temperature was not sufficiently rapid to prevent altogether its use, but the accuracy attainable was not of course as great as in the case of a reading at a stationary temperature. The great quickness with which the micrometer could be moved and set was the only excuse for using it.

The measurement of the pressure coefficient was conducted in the following manner. Having placed the thermometer in position, with the water in the vessel around the thermometer a few degrees cooler than the room, and the bottle having been previously exhausted of air to a pressure of about 4 to 6 cm. by means of a water pump, readings were begun. First a reading was taken at the atmospheric pressure. Then the tube containing the thermometer was connected with the manometer and the exhausted bottle, and after waiting a sufficient interval to allow the

meniscus to become a rising one, which interval was occupied in reading the manometer, another reading was taken. Then the manometer and bottle were cut off, and the atmospheric pressure again admitted to the tube, and a third reading taken. The intention was to make readings at about equal intervals, although these intervals were not measured except by estimation. In reducing the observations, the readings at atmospheric pressure were taken in pairs, one on each side of a reading at reduced pressure, and the average of these two was compared with the reading at reduced pressure in between. This gave the difference in height of the mercury column due to the pressure measured by the manometer. This process of measurement was repeated many times, as shown in the table, (Table 6 p.58). The sum of the differences of the thermometer readings was divided by the sum of the pressures observed, and the quotient is the coefficient of exterior pressure, β_e . The probable error was also calculated, following Guillaume. It gave an idea of the accuracy of the measurement. The table, No. 6, p.58 ,gives the measurements made on the three Baudin thermometers. The results are as follows, the unit being degrees depression due to a pressure of 1 mm. of mercury. For convenience, the centimeters on the stem of the Baudin thermometers are called degrees.

For Baudin 6163. $\beta_e = 0.000247$

For Baudin 6165. $\beta_e = 0.000347$

For Baudin 6166. $\beta_e = 0.000411$

b. Interior pressure coefficient.

In getting the coefficient of internal pressure, the International Bureau, as mentioned before, calculates it from the external pressure coefficient. It differs from it by a small quantity. When the thermometer is made of French hard glass, and is graduated in degrees, the coefficient of internal pressure is connected with the external coefficient by the equation

$$\beta_i = \beta_e + 0.000\ 015\ 4$$

where the unit of measurement is degrees Centigrade per millimeter of mercury pressure. Part of this coefficient depends on the cubical compression of mercury, and part on that of the glass. The Baudin thermometers are not made of French hard glass, but it is probable that this difference would not be much changed by this fact. The same value has therefore been used. It must be remembered that the Baudin thermometers are not graduated in degrees, but in centimeters. The values of the degree in the unit of division of the stem, that is, in centimeters, are as follows:

For Baudin 6163, 0.8976 cm. $= \alpha$

For Baudin 6165 1.1805 cm. $= \alpha$

For Baudin 6166, 1.2836 cm. $= \alpha$

The reciprocals of these numbers would give the number of degrees corresponding to a centimeter. In the case of these Baudin thermometers, instead of the relation given above, we would have, if $k = 0.000\ 015\ 4$

$$\beta_i = -\beta_e + \alpha k$$

This gives therefore, for the three thermometers, the following values of β_i.

For Baudin 6163 $\beta_i = 0.000261$
For Baudin 6165, $\beta_i = 0.000366$
For Baudin 6166, $\beta_i = 0.000431$

There is no doubt that it would be better to find this coefficient by experiment. This is sometimes done, as described in Vol. 1, of the Wiss. Abhand. Phys.Tech.Reichanstalt, at Charlottenburg. The method is to place the thermometer in a hypsometer which can be placed, and the thermometer read, either vertically or horizontally. The errors of capillarity, etc., must come in to a considerable extent in this method. The Reichanstalt measured β_i in several thermometers, and obtained the following results for the difference of the two coefficients. These differ a good deal from the theoretical value, but it seems as if this difference might be more easily due to errors in measuring the value of β_i, than to a real difference. Table 7, p. 63.
The table is taken from p. 79 of the volume mentioned above.

7. Manner of making the comparisons.

In comparing a Tonnelot thermometer with one of the Baudin thermometers, the Baudin was placed first in ice for about two or three hours. Its zero point was then read by means of the micrometer telescope three or four times in succession, and the average reading taken. In the mean time, the water in the comparison tank, having been cooled to about 10° or lower, the Baudin and one of the Tonnelot thermometers were placed in the tank. The top of the tank was put on, and the water was thoroughly stirred with the inner box containing the bulbs open. As long as the temperature of the water in the tank was lower than that of the room, it of course rose very slowly while the stirring went on. This sufficed to make the thermometers always reach any given temperature with a rising meniscus. As soon as the water was thoroughly mixed, the stirring was stopped and the inner box immediately closed. A micrometer reading of the position of the mercury thread on one of the thermometers was then taken quickly, the telescope shifted to the other thermometer, and a reading taken of it. A second reading of both thermometers was also taken. Of course the first readings were the most reliable, but when there was no delay, there was hardly ever any appreciable change of temperature observed on reading the second time, except sometimes at the extreme temperature of 40°. The second reading was taken more as a check on the first to make sure there was no error

in reading, etc., but it generally, although not always, agreed so well with the first that it was almost always averaged up with it. The difference between the two readings taken in this way hardly ever amounted to more than 0°.001, and was usually less. A large part of this was certainly due to the difficulty of setting on the division lines, and not to any change in the thermometers, as equally large errors were made in measuring the distance apart of the division lines. These division lines on the Baudin thermometers occupied quite a large part of the interval between two successive lines, say about 0.07 mm. out of 1 mm.

Having made this observation at a certain temperature, the inner box was opened, the water stirred up again, and another comparison made in the same way. This would be of course at a slightly higher temperature. These readings at two nearby temperatures were averaged and the average regarded as one reading. When the temperatures were higher than that of the room, the only difference made was that steam was passed into the heating tube just before a reading was taken. The water was stirred, and the thermometers were brought to the position in which they were to be read with a rising meniscus, and not with a falling one. This was made very sure by observing one of the thermometers through the telescope while the heating and stirring was going on. Having made two observations at nearby temperatures, the top of the tank was removed, and the Tonnelot thermometer taken out and its zero determined.

The Tonnelot was then replaced, the top of the tank put on, the water heated, and a comparison made in the same way at the next temperatune. It was not possible conveniently to make ~~many~~ comparisons at many points in one day. The intention was therefore to take observations roughly at 10°, 20°, 30°, and 40°. This was only approximately carried out, as it sometimes became convenient for a good many reasons to use temperatures intermediate to these.

8. Comparisons made, and resulting curves.

The following series of comparisons were made, not however in the order here described. At the end of the paper will be given the original micrometer readings in the case of one of the comparisons so as to show the manner of working up the results. In the other cases, however, only the actual readings of the thermometers as deduced from the micrometer readings will be given.

Two comparison were made between Tonnelot 11801 and Tonnelot 11811, and three between Tonnelot 11800 and Tonnelot 11811. In one of the latter comparisons, the thermometer 11811 became accidentally heated up to 30° before a reading at 20° was taken, and for this reason, on account of the recovery of the zero being in progress while the comparison was being made, it was thought probable that some irregularity would be shown. This proved to be the case, so this comparison, that of 21 April, was rejected. In comparing the Tonnelot thermometers, they were

always placed in ice for some hours before the comparisons were begun, in case the first temperatures used were lower than the temperature to which the thermometer had been exposed for some time previously, so that the recovery of the zero might have a chance to proceed as far as possible before the comparisons were begun. The results of the comparisons of the Tonnelot thermometers with each other are given on p.64, Table 8 , and the curves corresponding are given on p.45 . The curves of the differences between the thermometers in each pair were plotted, and from these a smooth curve was drawn in each case, and the ordinates tabulated on p.74 , Table 9 . From these, a table of corrections was drawn up for every degree of the scale, so that the indications of Tonnelot 11300 and Tonnelot 11811, the repaired thermometers, could be reduced to those of 11801. The corrections were generally rather small, amounting to only a few thousandths of a degree in most cases. These are given in Table 9.p. 74.

Next a series of comparisons was made of each Tonnelot thermometer with each Baudin. The original and reduced readings of these comparisons are given in the table 10, p.75. The differences between the Tonnelot and the Baudin thermometers were regarded as corrections to be applied to the Baudin thermometers when reduced to the absolute scale by Rowland's table, to make them agree with the Tonnelot hydrogen scale. In calculating temperatures on the hydrogen scale, the corrections supplied by the International Bureas were applied, and finally these readings were corrected by the differences found between the

Tonnelot thermometers by the direct comparison together. These final corrected values, as given in Table 11. p.81, were used to plot correction curves for each Baudin thermometer, as shown on p. 46. One comparison was made between each possible pair, and finally an additional one between Tonnelot 11801, and Baudin 6163. At the time this latter was made, the Baudin had not recovered yet from the depression of its zero caused by its having been in use six days before at a temperature of 40°. Its curve differed from the others in the way that might have been expected, but, as it had the same general form, it was regarded as a verification of the others, although it was rejected because proper allowance could not be made for the abnormal depression of the zero point. These comparisons therefore gave three curves for each Baudin thermometer, each one corresponding to one of the Tonnelot thermometers. The curves as drawn show only the points found by observation connected by straight lines. From these curves, or rather from the equivalent smooth curves, an average curve for each Baudin thermometer was drawn, as represented on p. 47. This gave the final correction curve for each Baudin thermometer. The ordinates corresponding are given in Table 12. p. 84. These ordinates represent the average value of the correction that must be applied to the indications of the Baudin thermometers, when reduced by Rowland's table, p. 25. to the absolute scale, to make them agree with the hydrogen scale as represented by the Tonnelot thermometer 11801. These were finally used to calculate the effect on the value

of the mechanical equivalent of heat, in the way to be explained presently.

In order to get a still further check on the comparisons, the three Baudin thermometers were placed in the tank at the same time, and a series of comparisons was made between them in pairs. The zeros were all determined in the usual way before the series was begun. In the neighborhood of each temperature, comparisons were made in three pairs. 6163 was compared with 6165, the water was stirred up, and at a temperature only slightly different, 6165 was compared with 6166. Then at a third temperature only slightly different from this, 6163 was compared with 6166. Of course at these three temperatures which are practically the same, the third comparison ought to show an agreement with the other two. Calling B_3, B_5, and B_6 the three reduced readings compared, leaving out of account the slight difference, we get a measurement of $(B_3 - B_5)$, $(B_5 - B_6)$, and then of $B_3 - B_6$ If no error had been made, the relation would hold

$$(B_3 - B_5) + (B_5 - B_6) = B_3 - B_6$$

This was never exactly the case. The difference was distributed over the three measurements where it was enough to amount to more than 0.001 C., so that the observations would be concordant. The comparisons of these three thermometers made in this way agree practically with the comparisons made indirectly through the three Tonnelot thermometers. The results are given in Table 13, p.86. To show the agreement, curves were drawn representing the comparisons on the same plan as the

correction curves before shown, p 47. The correction curve of Baudin 6163 was assumed, and from this the correction curves of the other thermometers were deduced from the comparison made. These curves are shown on the same sheet as the mean correction curves, p. 47. Also Table 14, p. 88.

9. Calculation of the effect on Rowland's value of the mechanical equivalent of heat.

In order to estimate the effect on the value of the mechanical equivalent of heat of applying these corrections to the Baudin thermometers, the experiments made on each thermometer, and the corrections for each thermometer, were considered separately. Rowland gives a table on p. 192 of his paper on the mechanical equivalent, giving the mechanical equivalent, in kilogram-meters at Baltimore, each value calculated from a rise of 10° in the temperature. This table is given here on p. 89. Table 15, the experiments being classified, however, according to the thermometer used. From this table, at each temperature, and for each thermometer separately, the mean value of the mechanical equivalent was deduced. Rowland's value of the mechanical equivalent was deduced from an equation of the form

$$J = \frac{W}{10^\circ}$$

where W is a certain number of ergs. J at 12°, for example, was calculated from the value of W in going from 7° to 17° C. That is,

$$J_{12} = \frac{W}{17^\circ - 7^\circ}$$

If C_{17} and C_7 are the corrections found for the readings on the Baudin thermometer, to reduce them to the hydrogen scale, these corrections applied to the value of J_{12} will give the corrected value of J_{12} which we have called J'_{12}. This gives

$$J'_{12} = \frac{W}{17 + C_{17} - (7 + C_7)} = \frac{W}{10^\circ + C_{17} - C_7}$$

$$\therefore \quad J'_{12} = \frac{W}{10} \cdot \frac{10}{10 + C_{17} - C_7} = J_{12} \frac{10}{10 + C_{17} - C_7}$$

When $C_{17} - C_7$ is very small, as is always the case in these corrections, this may be written,

$$J'_{12} = J_{12}\left(1 - \frac{C_{17} - C_7}{10}\right) = J_{12} P_{12}$$

where

$$P_{12} = \left(1 - \frac{C_{17} - C_7}{10}\right) = \left(1 + \frac{C_7 - C_{17}}{10}\right)$$

This conversion factor, P_{12}, was calculated for each degree of the scale where it was necessary, and for each thermometer, and the corresponding value of J' calculated. Then, taking account of the number of observations on each thermometer, used in getting the average value of J, these corrected values were averaged for each degree at which observations were made. The resulting values are given in Table 16, p 91. These values were plotted, and a smooth curve drawn in the neighborhood of the points. The ordinates deduced from this smooth curve give the corrected value of the mechanical equivalent in kilogram-meters at Baltimore, as deduced from the comparisons described here. Table 16, p. 91. The curves on p. 48, show the final values given by Rowland, deduced from a smooth curve, and the corrected values. On p. 49, the same curves are drawn, but the ordinates are reduced to their value in the C.G.S. system. On the same

diagram are given the values obtained by Griffiths, correcting his value to the hydrogen scale. Schuster and Gannon's value is also shown on the same diagram.

Griffiths' value of the mechanical equivalent, after having several small corrections applied, is given by him as

$$J = 4.198 \left(1 - 0.000266(t^\circ - 15^\circ)\right) \times 10^7$$

between 15° and 26° C., in C.G.S. units, on the Paris nitrogen scale. (Phil. Mag., 40.447, and 437, 1895.) To reduce to the hydrogen scale, the calculation was made as follows.

Let

J_N = the mechanical equivalent on the nitrogen scale.

J_H = the mechanical equivalent on the hydrogen scale.

From the definition of the mechanical equivalent, we have

$$J_N = \frac{dW}{dt_N} \qquad \text{and } J_H = \frac{dW}{dt_H}$$

At each point of the scale, let

$$dt_N = R\,dt_H \quad \therefore \; J_N = \frac{dW}{R\,dt_H} \text{ and } RJ_N = \frac{dW}{dt_H} = J_H$$

Also, $R = \dfrac{dt_N}{dt_H}$

Values of R were calculated for a number of points of the scale, from the tables given by Guillaume, "Thermometrie de Precision", p. 258, giving the differences between the

nitrogen and hydrogen scales, from the experiments of Chappuis. These values are as follows:

At 2°.5	R = 1.0006
7°.5	1.0006
10°	1.0005
12°.5	1.0004
17°.5	1.0004
20°.	1.0003
22°.5	1.0002
25°.	1.0001
27°.5	1.

From these values of R and from Griffiths' formula, we get the following values of the mechanical equivalent:

	Nitrogen scale	Hydrogen scale.
At 15°	4.198×10^7	4.1997×10^7
20°	4.192×10^7	4.1932×10^7
25°	4.137×10^7	4.1374×10^7

These are the values used to plot the curve on p. 49.

10. Schuster's indirect comparison of Baudin 6166 with the Paris nitrogen thermometer.

Before the comparisons described here, one of Rowland's thermometers had already been compared indirectly with the Paris nitrogen thermometer. In the summer of 1879, Joule himself made a comparison of Rowland's thermometer, Baudin 6166, with his thermometer, and the results were publisned by Rowland in the Proceedings of the American Academy, Vol. 16, p. 38, 1880 -81. In 1892 -94, Schuster made a comparison of Joule's thermometer with a Tonnelot thermometer which had been standardized by the International Bureau, and he reduced the indications of the Joule thermometer to the Paris nitrogen scale. (Schuster, Phil. Mag. 39.477 1895). These two comparisons should give a means of reducing the indications of Rowland's thermometer to the Paris nitrogen or hydrogen scale.

In discussing Joule's comparison, Rowland derived an equation giving the temperature on the air thermometer, calculated from his Baudin 6166, as a function of the second degree of the temperature on Joule's thermometer. The writer however found it more convenient, for the present purpose, to use a graphic method. All the observations, therefore, were plotted on coordinate paper, graduated to millimeters, as represented on p. 50 The abscissae are temperatures on the air thermometer, according to 6166, each degree being represented by 5 mm. The ordinates are

values of the excess of the readings of Joule's thermometer above those of Rowland's air thermometer. For the ordinates each millimeter represents $0^\circ.001$. Through the points thus plotted, a smooth curve was drawn, passing necessarily through the zero point. This curve is the one called $T_J - T_{RA}$ where T_J means the temperature as given by Joule's thermometer. and T_{RA} the temperature by Rowland's air thermometer. From Schuster's comparison were taken, for a number of points on the scale, the differences between the readings of Joule's thermometer and the Paris nitrogen thermometer. These differences are values of the quantity that can be called conveniently $T_J - T_N$. Subtracting the values of this quantity at each point from the ordinates of the curve $T_J - T_{RA}$, we get a series of ordinates representing points on the curve $(T_N - T_{RA})_J$ thus

$$T_J - T_{RA} - (T_J - T_N) = (T_N - T_{RA})_J$$

These points were rather scattered, but a curve was drawn, estimating by the eye as nearly as possible its proper place. This curve represents the excess of the indications of the Paris nitrogen thermometer over those of Rowland's air thermometer, as given by Baudin 6166, through the indirect comparison by means of Joule's thermometer. On the same sheet there was next drawn a curve, $T_{Abs} - T_{RA}$, in which the ordinates represent the corrections that Rowland applied to his air thermometer scale to reduce it

to the absolute scale. To each ordinate of this curve was added the ordinate of the curve $T_H - T_{Abs}$ as given by the curve in this paper, p. 47. This gives

$$T_{abs} - T_{RA} + T_H - T_{abs} = T_H - T_{RA}$$

which is the excess of the Paris hydrogen scale above the indications of Rowland's air thermometer scale. To each of these ordinates there was added the values of $T_N - T_H$, the excess of the nitrogen over the hydrogen scale, as given in Guillaume, "Thermometrie de Precision", p. 253. This gives

$$T_H - T_{RA} + T_N - T_H = \left(T_N - T_{RA}\right)_T$$

which means the excess of the readings of the Paris nitrogen thermometer, as given by the Tonnelot 11801, over Rowland's air thermometer scale, as given by Baudin 8166. If no error of any kind had been made in the comparisons, these two curves, $\left(T_N - T_{RA}\right)_J$ and $\left(T_N - T_{RA}\right)_T$ would agree. The former is, however, considerably higher than the latter, although it is a curve of the same general form. The maximum ordinate of $\left(T_N - T_{RA}\right)_T$ is 0°.03, while that of the other curve is about 0°.05.

11. Conclusion.

The comparisons described in this paper seem to show, assuming the Paris hydrogen scale and the absolute scale to be practically the same, that Rowland's principal thermometer, Baudin 6163, when reduced to the absolute scale by his tables, reads a little too low up to about 27°, with a minimum at about 13° of about - 0°.009. Above 27°, it reads a little too high, reaching + 0°.013 at 40°. The other thermometer whose readings are important, Baudin 6166, reads a little too low at all points of the scale, reaching a minimum of about - 0°.025 at 20°. The third thermometer, which affected only one of the experiments on the mechanical equivalent, reads too high at all points of the scale, reaching as much as + 0°.05 at 30°.

The resulting changes on the mechanical equivalent have been to leave the value the same at 14°.5, to lower it below that point, and to raise it, above that point. The net change at 10° has been about 1 part in 1700, at 20°, 1 part in 1200, and at 25°, 1 part in 1000. These are certainly very small. This change has made the resulting value for the variation of the specific heat of water practically identical with that of Griffiths', as shown on the curve, p. 49. For the sake of comparison, Bartoli and Stracciati's value for the specific heat of water has been plotted on the same sheet, taking the specific heat at 15° as 1.

If, therefore, from the two experiments, that of Griffiths' by an electrical method, and that of Rowland by a mechanical method, with the corrections applied, curves representing the specific heat of water between 15° and 20° were drawn, taking the value of the mechanical equivalent at 15° in each case as unity, the two curves would be practically identical. This seems to indicate the possibility that the difference between Rowland's and Griffiths' value of J may be due to some error in the electrical standards used, or to some error in Rowland's measurement of the mechanical energy.

The question has been raised whether Rowland's thermometers could have suffered any change in their scale since they were compared with the air-thermometer in 1877-78, nearly twenty years ago. This could only be detected now if there had been also some relative changes among the several thermometers, so that they no longer agreed as formerly. The changes of the zero points since 1878 are as follows

For 6163 + 0.210 cm. =+0°.23
6165 + 0.328 cm. = +0°.3
6166 + 0.384 cm. = +0°.3

The bulb of a thermometer contains approximately 6250 degrees and this change of zero indicates a change in the volume of the bulb. Supposing, as seems reasonable, that the stems of the thermometers suffer a proportionate change, this would give an error at the upper part of the scale

for 6163, at 40° of + 0°.002
6165, at 30° of + 0°.0015
6166, at 30° of + 0°.0015

Such an error would be too small to affect these comparisons.

In the "thermometer book" of the Johns Hopkins University are some comparisons of these Baudin thermometers made at several previous dates. In order to see whether these comparison showed any evidence of a change in the thermometers, a number of these in 1880, and in 1886 were examined. It is impossible to say now with just how much care these comparisons were made. The author has reduced

a number of them, taking account of the change of zero, and the pressure of the water in the comparison tank, using the tables for reduction to the absolute scale given in Rowland's paper on the mechanical equivalent. Considering the discrepancy existing between the comparisons made at neighboring dates, these comparisons do not give any certain evidence of any relative change in the thermometers since those dates. On p. 57. are plotted curves showing the differences in the indications of these thermometers as deduced by the comparisons with the Tonnelot thermometers just completed, and those made at the earlier dates referred to.

Schuster's indirect comparison of Baudin 6166 gives a larger departure from the Paris nitrogen scale than do these last more direct comparisons, but the difference curve is of the same general form, and the discrepancy is not any greater than one would expect, considering all the possibilities of error. It is not known just how Joule made the comparison of his thermometer with Baudin 6166, but it is probable that he followed, in a general way, the plan used by Rowland.

It is safe to say, therefore, that the results given in this paper represent substantially the effect on Rowland's value of the mechanical equivalent of heat of a reduction of the readings of his thermometers to the Paris hydrogen scale.

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Plate 1. Comparison of Tonnelot thermometers

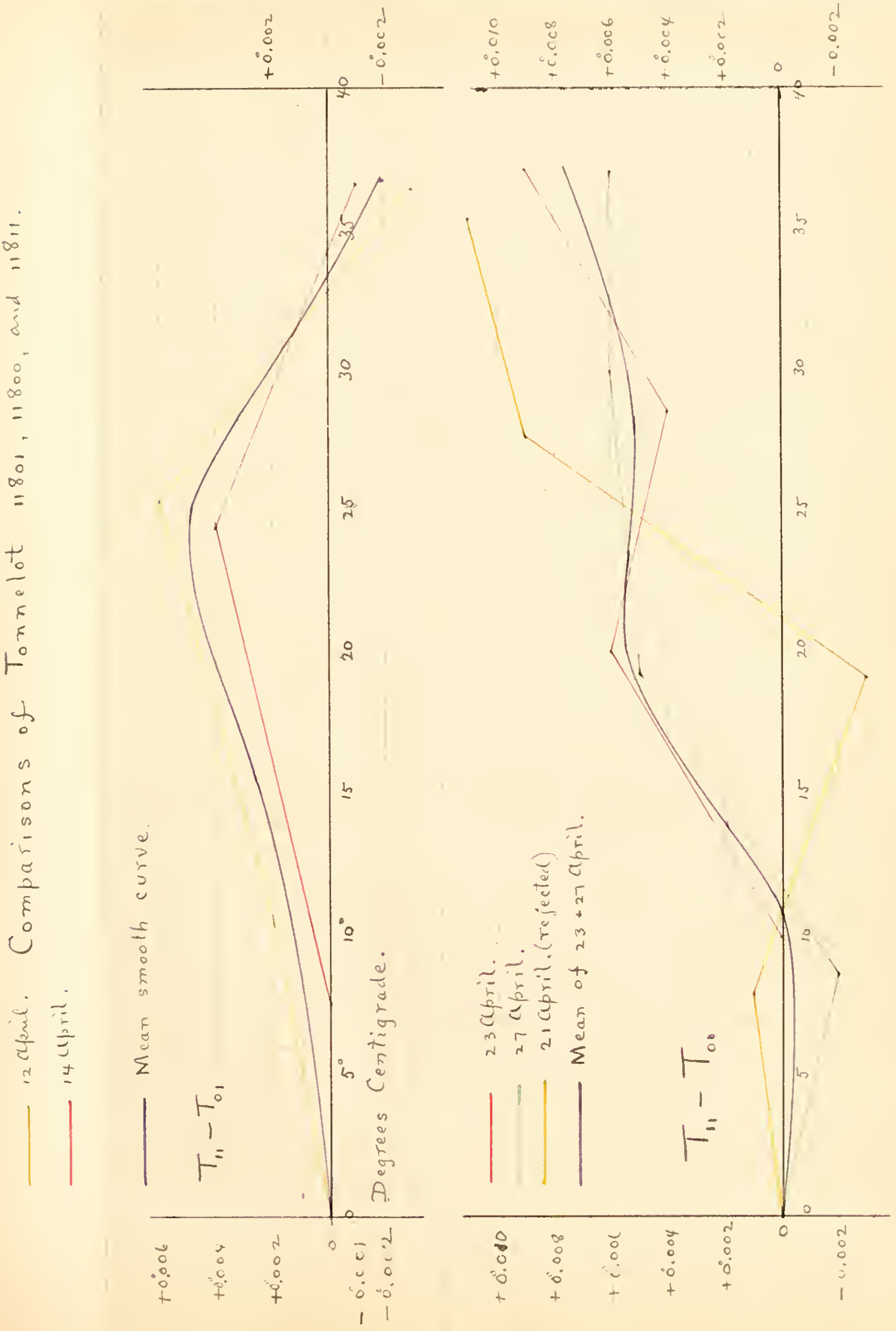


Plate 2. Comparisons of Baudin and Tonnelot thermom

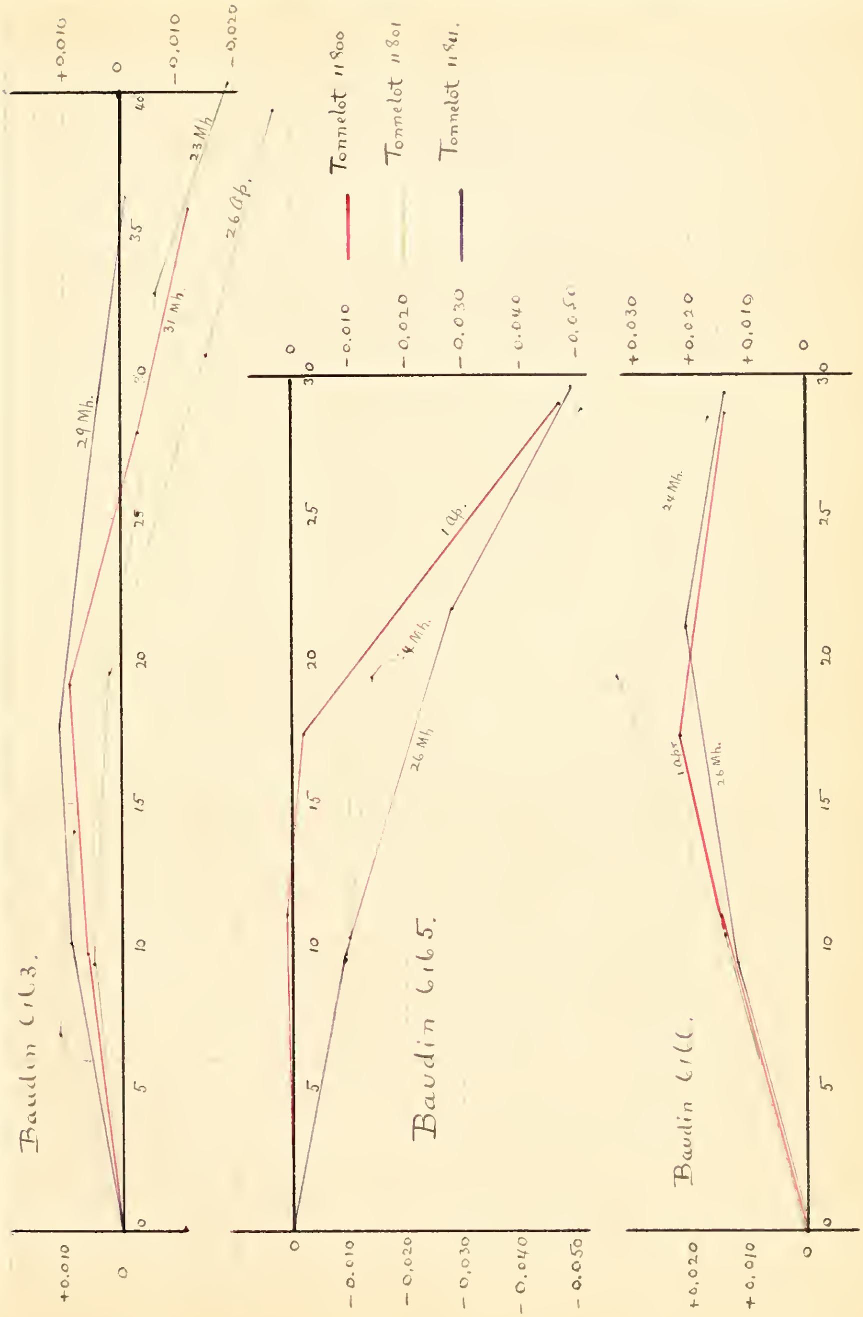


Plate 3. Correction curves for Baudin thermometers.

Correction curves for Rowland's Baudin thermometers.

Abscissae are temperatures on absolute scale. Ordinates are corrections to make Baudin thermometers, when readings are reduced to absolute scale, agree with the Paris Hydrogen thermometer.

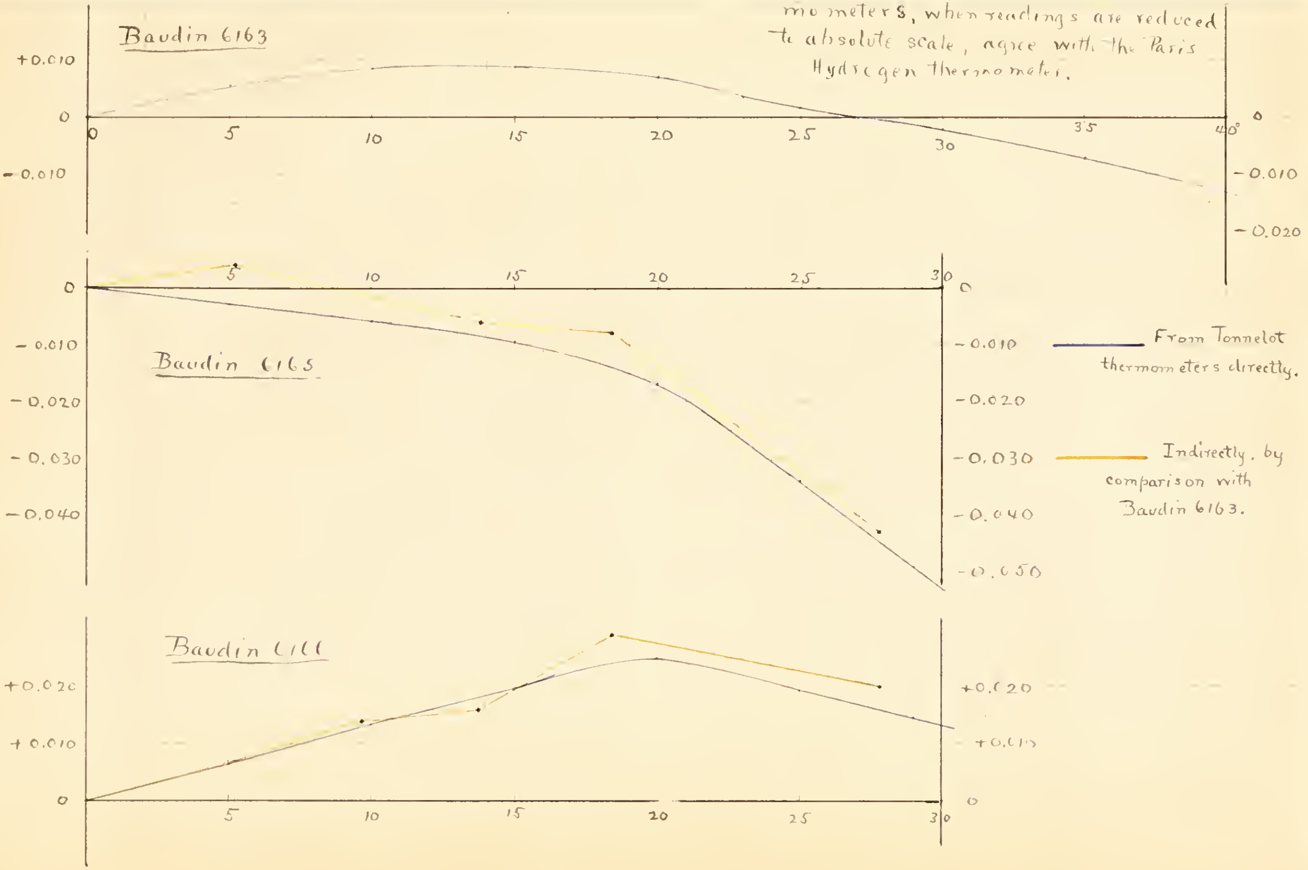


Plate 4.

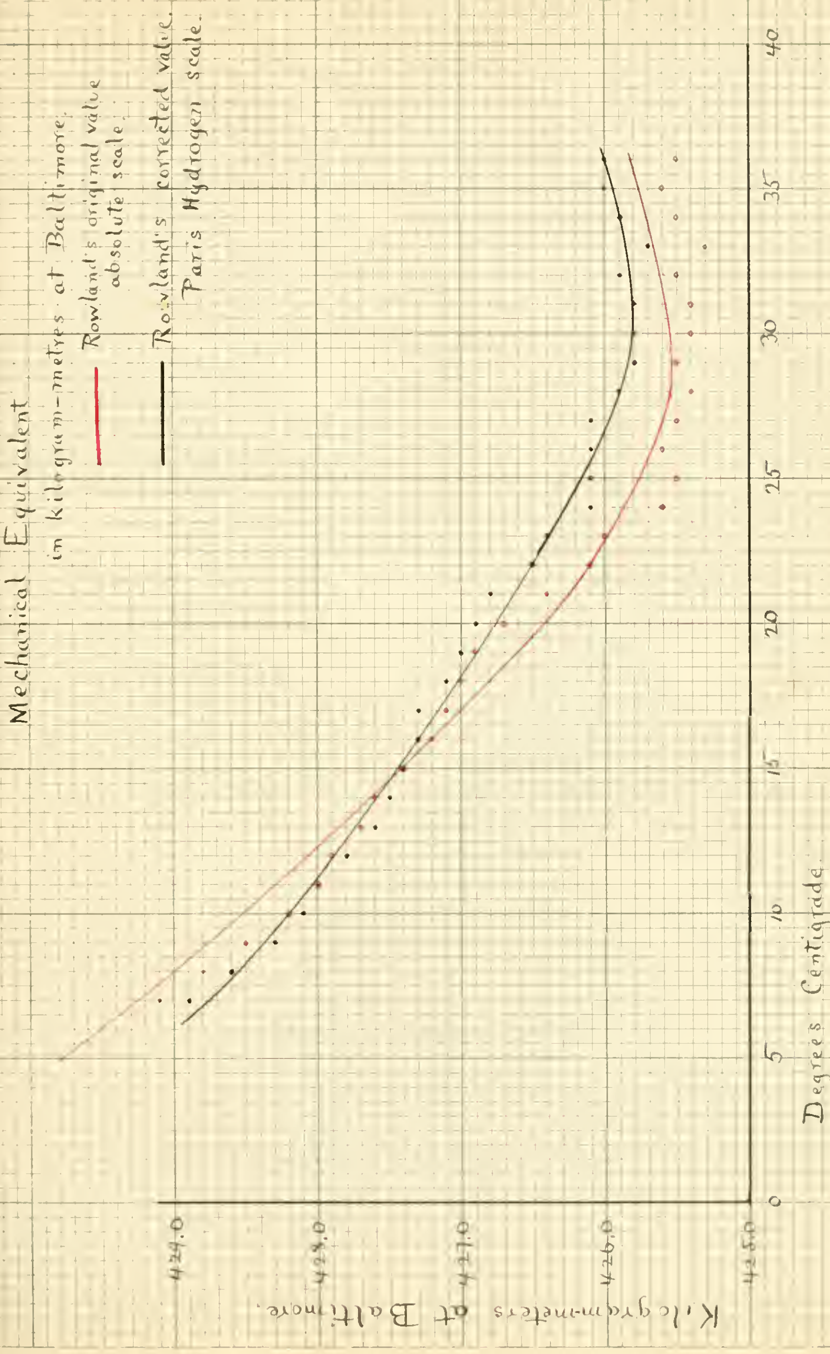

Mechanical Equivalent
in kilogram-metres at Baltimore.
Rowland's original value
absolute scale.
Rowland's corrected value.
Paris Hydrogen scale.
0
5
10
15
20
25
30
35
40
Degrees Centigrade
425.0
426.0
427.0
428.0
429.0
Kilogrammeters at Baltimore.

Plate 5.

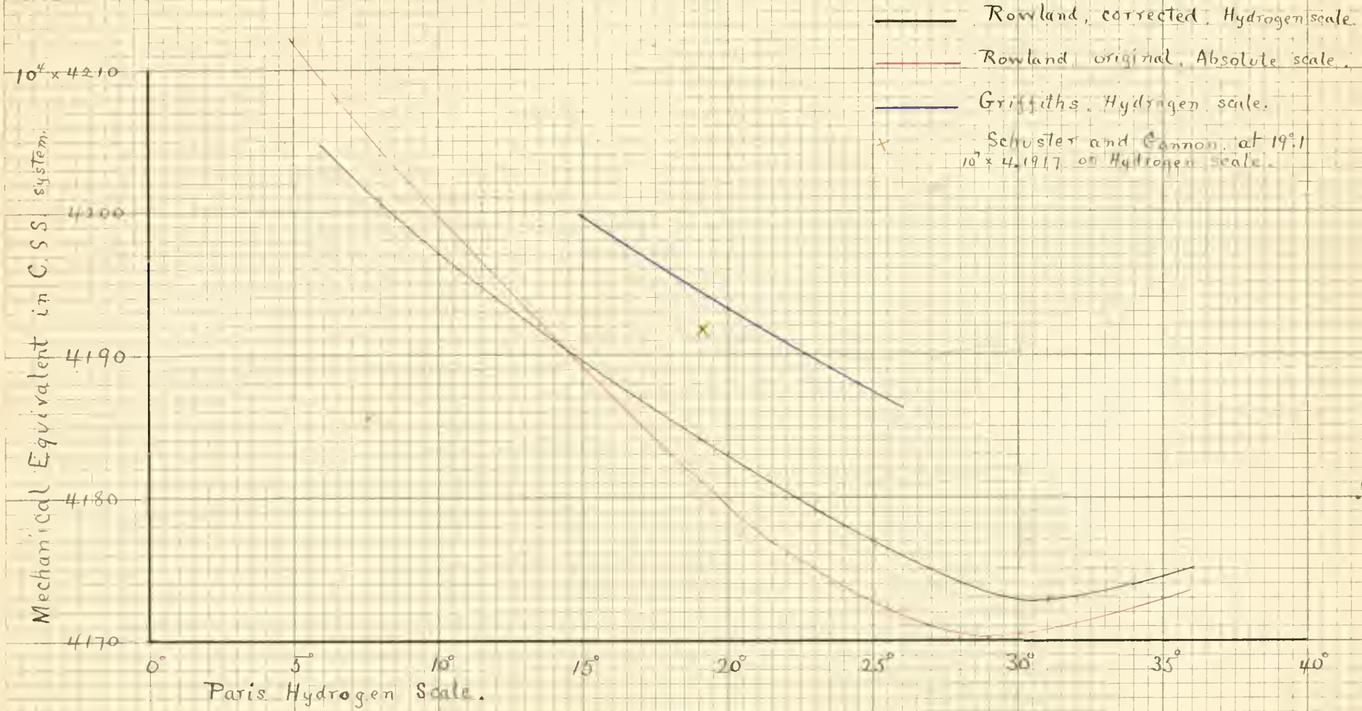

Rowland, corrected. Hydrogen scale.
Rowland original. Absolute scale.
Griffiths. Hydrogen scale.
× Schuster and Gannon. at 19°.1
10⁴ × 4.1917 on Hydrogen scale.
10⁴ × 4210
4200
4190
4180
4170
Mechanical Equivalent in C.G.S. system.
0°
5°
10°
15°
20°
25°
30°
35°
40°
Paris Hydrogen Scale.

Plate 6. Schuster's indirect comparison of Baudin [illegible]

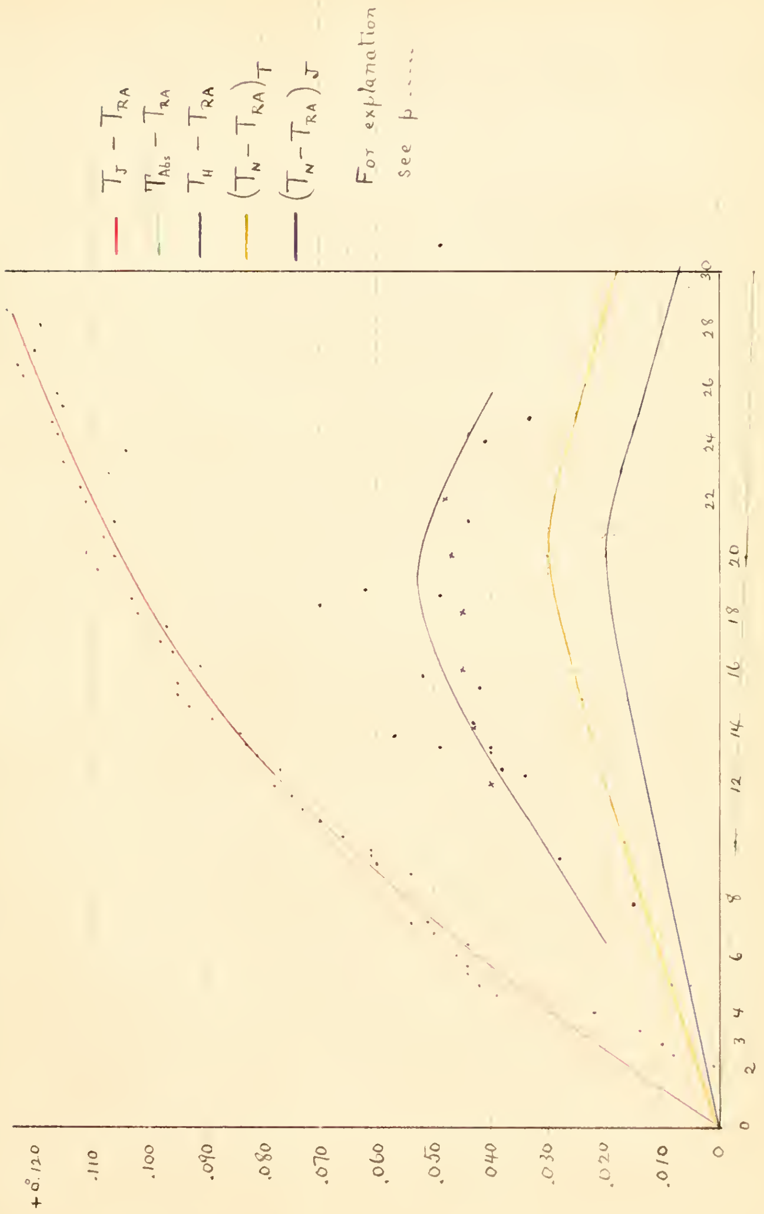
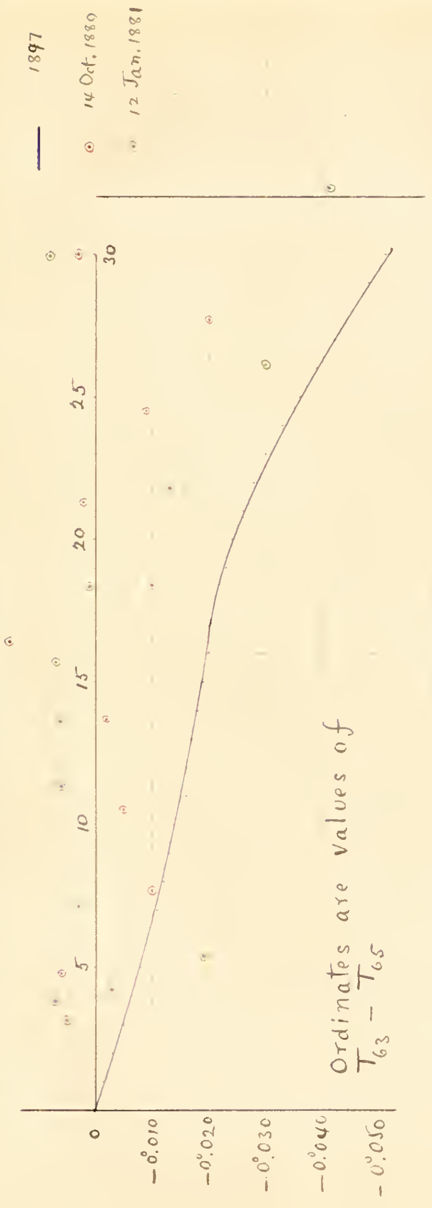


Plate 7. Differences between Baudin thermomete



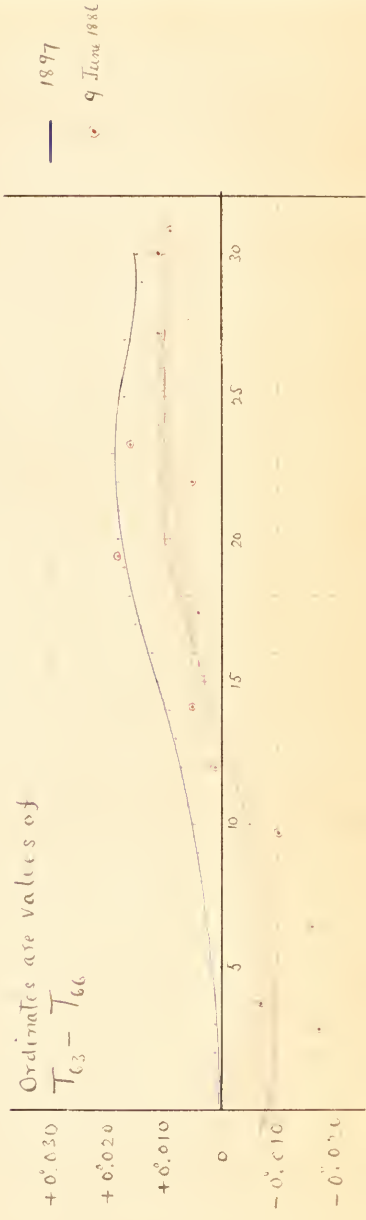


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TABLE 2.

Comparison of the Tonnelot thermometers, 11801, 11811, and 11800, with the standards of the International Bureau.

Tonnelot 11801.

Mean temperatures.	Tonnelot 11801.
9°.931	M + 0°.005
29°.865	M + 0°.006
49°.833	M + 0°.008

	Tonnelot 11811
19°.768	M - 0°.001
29°.774	M - 0°.001
49°.887	M - 0°.005

Tonnelot 11800.

A	B	C	D	E	F
19°.7170	20.6892	- 1.9980	22.6478	- 2.9308	- 0.0002
29.7747	32.2587	- 2.0011	34.2037	- 4.4290	- 0.0030
49.8870	55.3198	- 2.0245	57.2982	- 7.4108	+ 0.0030

Mean correction of a division - 0.129396

A--Mean corrected indications of thermometers4327 and 4330.
B--Uncorrected indication of thermometer 11800
C Uncorrected zero of thermometer 11800
D Corrected indication of thermometer 11800
E--Correction of thermometer 11800.
F- Difference [Ecart]

TABLE 3.

Reduction of Rowland's Baudin thermometers to the air thermometer, and to the absolute scale.

Baudin 6163

A	B	C
50	- 0.911	- 0.911
53.1	0	0
60	+ 0.214	+ 0.214
70	1.328	1.328
80	2.461	2.460
90	3.584	3.583
100	4.707	4.706
110	5.829	5.827
120	6.950	6.948
130	8.071	8.069
140	9.193	9.190
150	10.314	10.311
160	11.435	11.432
170	12.556	12.553
180	13.676	13.672
190	14.794	14.790
200	15.909	15.905
210	17.022	17.018
220	18.132	18.127
230	19.242	19.237
240	20.350	20.345
250	21.457	21.452
260	22.559	22.554
270	23.657	23.652
280	24.755	24.750
290	25.854	25.848
300	26.956	26.950
310	28.060	28.056
320	29.169	29.163
330	30.282	30.276
340	31.398	31.392
350	32.514	32.508
360	33.630	33.624
370	34.748	34.742
380	35.864	35.857
390	36.979	36.972
400	38.094	38.087
410	39.206	39.199
420	40.316	40.309

Column A Reading in millimeters on the stem.

Column B- Temperature on Air Thermometer.

Column C- Temperature on Absolute Scale.

TABLE 3, continued.

Baudin 6165

A	B	C
30	- 0.457	- 0.457
35	0	0
40	+ 0.457	+ 0.457
50	1.368	1.368
60	2.276	2.275
70	3.174	3.173
80	4.069	4.068
90	4.957	4.955
100	5.841	5.839
110	6.714	6.712
120	7.590	7.588
130	8.459	8.456
140	9.324	9.321
150	10.186	10.183
160	11.042	11.039
170	11.896	11.893
180	12.749	12.746
190	13.601	13.598
200	14.453	14.450
210	15.305	15.302
220	16.157	16.153
230	17.009	17.005
240	17.861	17.857
250	18.714	18.709
260	19.562	19.557
270	20.406	20.401
280	21.247	21.242
290	22.081	22.076
300	22.912	22.907
310	23.736	23.731
320	24.552	24.547
330	35.370	25.365
340	26.180	26.174
350	26.987	26.981
360	27.788	27.782
370	28.590	28.584
380	29.382	29.376
390	30.176	30.170
400	30.971	30.965
410	31.782	31.786
420	32.577	32.581

TABLE 3, concluded

Baudin 6166.

A	B	C	A	B	C
20	- 0.034	- 0.034	230	16.298	16.294
30	+ 0.759	+ 0.759	240	17.074	17.070
40	1.553	1.553	250	17.849	17.845
50	2.336	2.335	260	18.627	18.622
60	3.115	3.114	270	19.405	19.400
70	3.889	3.888	280	20.182	20.177
80	4.665	4.664	290	20.960	20.955
90	5.438	5.436	300	21.735	21.730
100	6.212	6.210	310	22.511	22.506
110	6.988	6.986	320	23.292	23.287
120	7.765	7.763	330	24.075	24.070
130	8.544	8.542	340	24.855	24.850
140	9.323	9.321	350	25.634	25.628
150	10.105	10.102	360	26.412	26.406
160	10.887	10.884	370	27.195	27.189
170	11.667	11.664	380	27.982	27.976
180	12.444	12.441	390	28.768	28.762
190	13.217	13.214	400	29.550	29.544
200	13.988	13.984	410	30.339	30.333
210	14.756	14.752	420	31.123	31.117
220	15.526	15.522	430	31.914	31.908

TABLE 4.

Reduction of Air Thermometer to Absolute scale.

(From p. 114, Rowland, Mech. Eq.)

Air thermometer.		Correction to air thermometer	
0°	40	0	-0.0067
10°	50°	-0.0028	-0.0068
20°	80°	-0.0048	-0.0044
30°	100°	-0.0061	0.

TABLE 6

Measurements on exterior pressure coefficients of the Baudin thermometers.

Baudin 6163 3 March 1897.

Mercury manom. reduced to 0°	Thermometer reading	means of pr. [illegible] 0 pressure	Observed differences	Calc. Difs.
0	21.296			
723.8 mm	21.121	21.300	0.119	.119
0	21.305			
691.1	21.137	21.310	.173	.172
0	21.315			
671.	21.153	21.318	.165	.166
0	21.322			
645.4	21.168	21.326	.158	.160
0	21.331			
622.5	21.183	21.335	.152	.154
0	21.340			
591.7	21.194	21.345	.151	.148
0	21.350			
570.9	21.208	21.353	.145	.142
0	21.357			
577.2	21.217	21.360	.143	.143
0	21.364			
573.3	21.224	21.369	.145	.142
0	21.374			
580.2	21.231	21.376	.145	.144
0	21.378			
579.5	21.339	21.381	.142	.143
0	21.385			
590.8	21.242	21.390	.148	.146
0	21.395			
7434.4			1.846	

Table 6, continued.

merc. manom. ed to zero	Therm. reading	means of pairs	Observed differences	Calc. Difs
7434.4			1.846	
0	21.395			
598.1	21.251	21.391	.146	.148
0	21.400			
598.3	21.256	21.403	.147	.148
0	21.401			
596.4	21.266	21.412	.146	.148
0	21.417			
595.8	21.272	21.419	.147	.147
0	21.422			
581.3	21.280	21.425	.145	.144
0	21.428			
589.8	21.286	21.432	.146	.146
0	21.436			
589.8	21.293	21.438	.145	.146
0	21.441			
588.8	21.300	21.444	.144	.146
0	21.447			
12173.3 β_e =			3.012	

$\therefore \beta_e = 0.0002474$ Baudin
± 4 6163

Table 6. continued

Baudin 6165. 5 March, 1897.

Mercury man. red. to 0°	Thermom. Reading	mean of Pairs	Observ. Difs	Calc Difs
0 mm	23.088			
665	22.868	23.094	.226	.231
0	23.100			
643	22.885	23.109	.224	.223
0	23.118			
622	22.909	23.127	.218	.216
0	23.135			
613	22.928	23.142	.214	.213
0	23.150			
604	22.948	23.157	.209	.209
0	23.164			
598	22.965	23.171	.206	.207
0	23.179			
594	22.982	23.187	.205	.206
0	23.196			
592	23.000	23.202	.202	.206
0	23.209			
585	23.015	23.218	.203	.203
0	23.228			
586	23.033	23.235	.202	.203
0	23.243			
584	23.049	23.251	.202	.203
0	23.260			
6686.			2.311	

Table 6 continued

Merc. manom. red. to 0°	Therm Reading.	Means of Pairs	Obsvd. difs	Calc Difs.
6686 mm.			2.311	
0	23.260			
580	23.065	23.268	.203	.201
0	23.277			
589	23.079	23.285	.206	.205
0	23.293			
594	23.093	23.302	.209	.206
0	23.311			
593	23.114	23.320	.206	.206
0	23.324			
591	23.131	23.338	.207	.205
0	23.347			
589	23.150	23.357	.207	.205
0	23.367			
598	23.166	23.375	.209	.207
0	23.384			
593	23.146	23.393	.207	.206
0	23.403			

$11413\, \beta_e = 3.965$

$\therefore \beta_e = 0.0003474$ Baudin

$\pm \quad 5$ 6165

Table 6, concluded.

Baudin 6166. 2 March. 1911.

Merc. manom. red to 0	Therm. Reading	Means of Pairs	Obsvd Difs	Calc. Difs
0 mm	24.147			
610.0	23.900	24.153	0.253	.251
0	24.159			
590.0	23.927	24.171	0.244	.243
0	24.183			
568.0	23.9545	24.190	0.236	.234
0	24.1975			
562.4	23.980	24.208	0.228	.231
0	24.218			
560.0	24.000	24.228	0.228	.230
0	24.238			
555.2	24.0135	24.246	0.232	.228
0	24.253			
535.2	24.038	24.258	0.220	.220
0	24.263			
515.8	24.0615	24.270	0.209	.212
0	24.2775			
497.8	24.0835	24.285	0.202	.205
0	24.2935			
480.0	24.1085	24.308	0.199	.197
0	24.3215			

$$5474.4\,\beta_0 = 2.251$$

$$\therefore \beta_0 = 0.0004110 \pm 1$$

Baudin
6166

TABLE 7.

Measurements of $\beta_i - \beta_e$ made at the Phys. Tech. Reichanstalt, at Charlottenburg. (Wiss. Abhand. Vol. 1, p. 79.)

Kind of glass.	Thermometers	$\beta_i - \beta_e$
Verre dur	4433	0.000 013 3
"	4437	0.000 008 3
"	4636^{II}	0.000 007 9
Jena 16^{III}	II	0.000 014 4
"	IV	0.000 012 9
"	V	0.000 011 8
"	VII	0.000 009 8
"	2	0.000 025 0
"	3	0.000 014 7
"	9	0.000 019 0
"	13	0.000 004 5

TABLE 8.

Comparisons of Tonnelot thermometers with each other.

12 April, 1897.	Tonnelot 11801	Tonnelot 11811
Barometer.	770 mm.	770 mm
Water, depth.	57 mm.	57 mm.
Ice, depth.	59 mm.	74 mm.
Observed zero.	+ 0.033	- 0.043
Corrected zero.	+ 0.039	- 0.033
Observed reading	10.529	10.615
Corrected reading. on hydrogen scale	10.421	10.423
Barometer.	771 mm.	771 mm.
Water, depth.	57 mm.	57 mm.
Ice, depth.	59 mm.	74 mm.
Observed zero.	+ 0.026	- 0.053
Corrected zero.	+ 0·032	- 0.044
Observed reading	25.470	25.981
Corrected reading.	25.338	25.344

The corrections applied in these reductions to the zero readings are those for calibration, interior pressure, and exterior pressure. Similar corrections are applied to the observed readings, and in addition, the zero correction, the fundamental-interval correction, the correction to reduce to the mean scale of the hard glass thermomet-

TABLE 8, continued.

ers, and the correction to reduce to the hydrogen scale.

	Tonnelot 11801	Tonnelot 11811.
Barometer.	771 mm.	771 mm.
Water, depth.	57 mm.	57
Ice, depth.	89 mm.	74
Observed zero.	+ 0.019	- 0.057
Corrected zero.	+ 0.025	- 0.048
Observed reading.	36.643	37.354
Corrected reading.	36.478	36.475

Comparison of 14 April, 1897.

Barometer.	759 mm	759 mm.
Water, depth.	57 mm.	57 mm.
Ice, depth.	69 mm.	64 mm.
Observed zero.	+ 0.035	- 0.041
Corrected zero.	+ 0.042	- 0.030
Observed reading.	7.681	7.682
Corrected reading	7.570	7.570

TABLE 8, continued.

	Tonnelot 11801	Tonnelot 11811
Bar.	757 mm.	757 mm.
Water.	57 mm.	57 mm.
Ice.	74 mm.	89 mm.
Ob. zero	+ 0.026	- 0.049
Cor. zero	+ 0.034	- 0.038
Ob. reading.	24.562	25.051
Cor. reading.	24.432	24.436

Bar.	756 mm.	756 mm.
Water.	57 mm	57 mm.
Ice.	74 mm.	89 mm.
Obs. zero.	+ 0.018	- 0.059
Cor. zero.	+ 0.026	- 0.048
Obs. reading.	36.725	37.438
Cor. reading.	36.560	36.559

TABLE 8, continued.

21 April.	Tonnelot 11800	Tonnelot 11811
Barometer.	772 mm.	772 mm.
Water, depth.	57 mm.	57 mm.
Ice, depth.	59 mm	84 mm.
Observed zero	- 1.934	- 0.043
Corrected zero.	- 1.928	- 0.033
Observed reading.	7.196	8.019
Corrected reading.	7.898	7.899

Bar.	771 mm.	771 mm.
Water.	57 mm.	57 mm.
Ice.	54 mm.	84 mm.
Obs. zero.	- 1.943	- 0.043
Cor. zero.	- 1.937	- 0.033
Obs. rdg.	20.180	19.610
Cor. rdg.	19.143	19.140

TABLE 8, continued.

	Tonnelot 11800.	Tonnelot 11811.
Bar.	771 mm.	771 mm.
Water.	57 mm.	57
Ice	44 mm.	74 mm.
Obs. zero.	- 1.945	- 0.050
Cor. zero.	- 1.939	- 0.041
Obs. rdg.	29.925	28.323
Cor. rdg.	27.593	27.607

Bar.	771 mm.	771 mm.
Water	57 mm.	57 mm.
Ice.	44 mm.	74 mm.
Obs. zero.	- 1.954	- 0.059
Cor. zero.	- 1.949	- 0.050
Obs. rdg.	38.783	36.165
Cor.rdg.	35.297	35.308

TABLE 8, continued.

23 April.	Tonnelot 11800.	Tonnelot 11811.
Bar.	766 mm.	766 mm.
Water.	57 mm.	57 mm.
Ice.	54 mm.	74 mm.
Obs. zero.	- 1.938	- 0.037
Cor. zero.	- 1.931	- 0.027
Obs. rdg.	9.523	10.079
Cor. rdg.	9.396	9.896

Bar.	763 mm.	763 mm.
Water.	57 mm.	57 mm.
Ice.	44 mm.	74 mm.
Obs. zero.	- 1.942	- 0.045
Cor. zero.	- 1.935	- 0.034
Obs. rdg.	21.231	20.553
Cor. rdg.	20.053	20.059

TABLE 8, continued.

	Tonnelot 11800.	Tonnelot 11811.
Bar.	763 mm.	763 mm.
Water.	57 mm.	57 mm.
Ice.	54 mm.	84 mm.
Obs. zero.	- 1.948	- 0.047
Cor. zero.	- 1.941	- 0.036
Obs. rdg.	30.961	29.246
Cor. rdg.	28.500	28.504

Bar.	763 mm.	763 mm.
Water.	57 mm.	57 mm.
Ice.	44 mm.	74 mm.
Obs. zero.	- 1.957	- 0.058
Cor. zero.	- 1.951	- 0.048
Obs. rdg.	40.879	38.022
Cor.rdg.	37.123	37.132

TABLE 8, continued.

27 April, 1897.	Tonnelot 11800	Tonnelot 11811
Bar.	756 mm.	756 mm.
Water.	57 mm.	57 mm.
Ice.	44 mm.	74 mm.
Obs. zero.	- 1.945	- 0.045
Cor. zero.	- 1.937	- 0.033
Obs. rdg.	7.966	8.702
Cor. rdg.	8.570	8.568

Bar.	756 mm.	756 mm.
Water.	57 mm.	57 mm.
Ice.	44 mm.	74 mm.
Obs. zero.	- 1.949	- 0.048
Cor. zero.	- 1.941	- 0.036
Obs. rdg.	20.299	19.725
Cor. rdg.	19.252	19.257

TABLE 8, continued.

	Tonnelot 11800	Tonnelot 11821.
Bar.	756 mm.	756 mm.
Water.	57 mm.	57 mm.
Ice.	44 mm.	74 mm.
Obs. zero.	- 1.957	- 0.055
Cor. zero.	- 1.950	- 0.044
Obs. rdg.	32.595	30.689
Cor rdg.	29.927	29.933

Bar.	755 mm.	755 mm.
Water.	57 mm.	57 mm.
Ice.	44 mm.	74 mm.
Obs. zero	- 1.962	- 0.059
Cor. zero.	- 1.955	- 0.048
Obs. rdg.	40.773	37.929
Cor. rdg.	37.035	37.041

TABLE 8, concluded.

Collected results of comparisons of Tonnelot thermometers together.

Tonnelot 11801.	Tonnelot 11811	$T_{11} - T_1$
10.421	10.423	+ 0.002
25.338	25.344	+ 0.006
36.478	36.475	- 0.003
7.570	7.570	0
24.432	24.436	+ 0.004
36.560	36.559	- 0.001

Tonnelot 11800	Tonnelot 11811	$T_{11} - T_0$
7.898	7.899	+ 0.001
19.143	19.140	- 0.003
27.598	27.607	+ 0.009
35.297	35.308	+ 0.011
9.896	9.986	0
20.053	20.059	+ 0.006
28.500	28.504	+ 0.004
37.123	37.132	+ 0.009
8.570	8.568	- 0.002
19.252	19.257	+ 0.005
29.927	29.933	+ 0.006
37.035	37.041	+ 0.006

(See curve of above on p. .

TABLE 9.

Differences between the Tonnelot thermometers, from the smooth curve.

Temp.	$T_{11} - T_{01}$	$T_{11} - T_{00}$	Corrections to reduce to scale of T. 11801.	
			T. 11800	T. 11811
2°	+ 0	0	0	0
4°	+ 0	0	0	0
6°	+ 0.001	0	- 0.001	-0.001
8°	0.001	0	- 0.001	- 0.001
10°	0.001	0	- 0.001	- 0.001
12°	0.002	+ 0.001	- 0.001	- 0.002
14°	0.002	+ 0.002	0	- 0.002
16°	0.003	+ 0.003	0	- 0.003
18°	0.003	0.005	+ 0.002	- 0.003
20°	0.004	0.005	+ 0.001	- 0.004
22°	0.005	0.006	+ 0.001	- 0.005
24°	0.005	0.005	0	- 0.005
26°	0.004	0.005	+ 0.001	- 0.004
28°	0.003	0.005	+ 0.002	- 0.003
30°	0.002	0.005	+ 0.003	- 0.002
32°	0.001	0.006	+ 0.005	- 0.001
34°	0	0.006	+ 0.006	0
36°	- 0.001	0.007	+ 0.008	+ 0.001
38°	- 0.002			

TABLE 10.

Comparisons of Baudin and Tonnelot thermometers.

As the surface of the water in the comparison tank was always 57 mm. (= 4 mm. mercury) above the bulbs of the thermometers, this fact will not be given in each table.

The number of millimeters corresponding to the word "ice", means, of course, the height of the surface of water in the zero tank above the middle point of the bulb of the thermometer.

Corresponding readings will be in the same vertical column. The abbreviations used in all the tables except the first, are indicated in the first.

23 March, 1897.	Tonnelot 11801		
A. Barometer	750 mm.	750	750
B. Ice.	59 mm.	59	59
C. Observed zero.	+ 0°.039	+ 0.038	+ 0.038
D. Corrected zero.	+ 0°.048	+ 0.047	+ 0.047
E. Observed reading.	7°.055	14.138	14.184
F. Corrected reading.	6°.941	14.027	14.073

Baudin 6163.

B. Ice.	94 mm.		
C. Observed zero.	6°.021		
D. Corrected zero.	6°.022		
E. Observed reading.	12°.236	18.578	18.619
F. Corrected reading.	11°.984	18.310	18.351
G. Absolute scale	6°.930	14.019	14.064

TABLE 10, continued.

Tonnelot 11801.

A.	748	748	747
B.	59	59	59
C.	+ 0.027	+ 0.025	+ 0.012
D.	+ 0.036	+ 0.034	+ 0.021
E.	25.335	33.044	40.509
F.	25.202	32.910	40.328

Baudin 6163.

B.			
C.			
D.			
E.	28.567	35.678	42.364
F.	28.414	35.366	42.034
G.	25.205	32.916	40.347

. . . .

29 March, 1897. Tonnelot 11811.

A.	765	765	765	765
B.	74	74	74	74
C.	- 0.040	- 0.047	- 0.055	- 0.063
D.	- 0.029	- 0.036	- 0.045	- 0.053
E.	10.329	18.166	29.969	37.227
F.	10.142	17.746	29.228	36.356

Baudin 6163.

B.	94			
C.	6.029			
D.	6.026			
E.	15.106	21.298	32.364	38.777
F.	14.840	21.664	32.053	38.449
G.	10.132	17.732	29.222	36.358

TABLE 10, continued.

31 March, 1897. Tonnelot 11800.

A.	764	764	764	764
B.	44	44	44	44
C.	- 1.935	- 1.942	- 1.949	- 1.952
D.	- 1.928	- 1.935	- 1.942	- 1.946
E.	9.361	20.231	30.385	39.410
F.	9.756	19.137	28.000	35.838

Baudin 6163

B.	94			
C.	6.021			
D.	6.018			
E.	14.756	23.228	31.255	38.320
F.	14.499	22.949	30.954	38.001
G.	9.749	19.130	28.005	35.858

. . . .

24 March

Tonnelot 11301

A.	740	740	740
B.	59	59	59
C.	+ 0.029	+ 0.022	+ 0.019
D.	+ 0.039	+ 0.032	+ 0.029
E.	10.442	19.568	28.854
F.	10.338	19.454	28.737

Baudin 6165

B.	75		
C.	3.323		
D.	3.328		
E.	15.586	26.327	37.731
F.	15.193	25.895	37.257
G.	10.348	19.468	28.788

TABLE 10, continued.

24 March, 1897. Tonnelot 11801

A.	740	740	740
B.	59	59	59
C.	+ 0.029	+ 0.022	+ 0.019
D.	+ 0.039	+ 0.032	+ 0.029
E.	10.521	19.573	28.645
F.	10.417	19.459	28.528

Baudin 6166.

B.	58		
C.	2.420		
D.	2.427		
E.	15.884	27.544	39.242
F.	15.385	27.034	38.681
G.	10.403	19.426	28.511

. . . . .

26 March, 1897 Tonnelot 11811

A.	756	756	756
B.	74	74	74
C.	- 0.050	- 0.054	- 0.056
D.	- 0.038	- 0.043	- 0.045
E.	9.624	22.358	30.301
F.	9.468	21.822	29.553

Baudin 6165.

B.	75		
C.	3.818		
D.	3.818		
E.	14.565	29.161	38.756
F.	14.130	28.723	38.282
G.	9.476	21.845	29.600

TABLE 10, continued.

26 March, 1897. Tonnelot 11811.

A.	756	756	756
B.	74	74	74
C.	- 0.050	- 0.054	- 0.056
D.	- 0.038	- 0.043	- 0.045
E.	9.613	21.795	30.190
F.	9.457	21.275	29.444

Baudin 6166

B.	58		
C.	2.417		
D.	2.417		
E.	14.610	29.896	40.415
F.	14.158	29.379	39.852
G.	9.444	21.249	29.428

. . . . .

1 April, 1897. Tonnelot 11800

A.	770	768	768
B.	44	44	44
C.	- 1.941	- 1.944	- 1.952
D.	- 1.935	- 1.938	- 1.947
E.	10.971	18.209	31.533
F.	11.154	17.432	29.001

Baudin 6165.

A.	770	768	768
B.	75	75	
C.	3.824		
D.	3.819		
E.	16.530	23.930	38.062
F.	16.132	23.506	37.586
G.	11.152	17.436	29.048

TABLE 10, continued.

1 April, 1897 Tonnelot 11800.

A.	770	768	768
B.	44	44	44
C.	- 1.941	- 1.944	- 1.952
D.	- 1.935	- 1.938	- 1.947
E.	10.861	18.171	31.143
F.	11.058	17.400	28.662

Baudin 6166

A.	770		
B.	58		
C.	2.418		
D.	2.412		
E.	16.664	24.896	39.417
F.	16.202	24.400	38.858
G	11.042	17.380	28.650

. . . .

26 April, 1897. Tonnelot 11801

A.	752	751	749	748
B.	79	59	69	59
C.	+ 0.033	+ 0.027	+ 0.018	+ 0.012
D.	+ 0.041	+ 0.036	+ 0.027	+ 0.021
E.	9.539	19.674	30.825	39.512
F.	9.432	19.555	30.707	39.331

Baudin 6163.

B.	114			
C.	6.006			
D.	6.006			
E.	14.454	23.550	33.691	41.454
F.	14.212	23.285	33.400	41.143
G.	9.428	19.553	30.722	39.358

TABLE 11.

Results of comparisons of Tonnelot thermometers and Baudin thermometers, collected from Table 10.

T. 11801	B. 6163.	Cor.
6.941	6.930	+ 0.011
14.027	14.019	+ 0.008
14.073	14.064	+ 0.009
25.202	25.205	- 0.003
32.910	32.916	- 0.006
40.328	40.347	- 0.019

T. 11811	T.11811 corr.	B.6163	
10.142	10.141	10.132	+ 0.009
17.746	17.743	17.732	+ 0.011
29.223	29.226	29.222	+ 0.004
36.356	36.357	36.358	- 0.001

T.11800	T.11800 corr.	B.6163	
9.756	9.755	9.749	+ 0.006
19.187	19.188	19.180	+ 0.008
28.000	28.002	28.005	- 0.003
35.838	35.846	35.858	- 0.012

T.11801	B.6163	
9.432	9.428	+ 0.004
19.555	19.553	+ 0.002
30.707	30.722	- 0.015
39.331	39.358	- 0.027

TABLE 11, continued.

T. 11801	B. 6165.	Corr.
10.338	10.348	- 0.010
19.454	19.468	- 0.014
28.737	28.788	- 0.051

T. 11811	T. 11811 corr.	B. 6165	
9.468	9.467	9.476	- 0.009
21.822	21.817	21.845	- 0.028
29.553	29.551	29.600	- 0.049

T. 11800	T. 11800 corr'd.	B. 6165	
11.154	11.153	11.152	+ 0.001
17.432	17.434	17.436	- 0.002
29.001	29.004	29.048	- 0.044

TABLE 11, continued.

Tonnelot 11801	Baudin 6166	Corr.
10.417	10.403	+ 0.014
19.459	19.426	+ 0.033
28.528	28.511	+ 0.017

T. 11811	T. 11811, corr.	Baudin 6166	
9.457	9.456	9.444	+ 0.012
21.275	21.270	21.249	+ 0.021
29.444	29.442	29.428	+ 0.014

T. 11800	T. 11800, corr.	Baudin 6166	
11.058	11.057	11.042	+ 0.015
17.400	17.402	17.380	+ 0.022
28.662	28.664	28.650	+ 0.014

TABLE 12.

Corrections to be added to the indications of Rowland's Baudin thermometers, when they are reduced by his tables to the absolute scale, to make them agree with the Paris hydrogen thermometer. These corrections were obtained from the smooth curve on p. 47 .

Baudin 6163

Temp.	Corr.	Temp.	Corr.
0	+ 0.	21	+ 0.006
1	+ 0.001	22	+ 0.005
2	+ 0.002	23	+ 0.003
3	+ 0.003	24	+ 0.002
4	+ 0.004	25	+ 0.002
5	+ 0.005	26	+ 0.001
6	+ 0.006	27	0.
7	+ 0.007	28	- 0.001
8	+ 0.0075	29	- 0.001
9	+ 0.008	30	- 0.002
10	+ 0.0085	31	- 0.003
11	+ 0.009	32	- 0.004
12	+ 0.009	33	- 0.005
13	+ 0.009	34	- 0.006
14	+ 0.009	35	- 0.007
15	+ 0.009	36	- 0.008
16	+ 0.009	37	- 0.010
17	+ 0.008	38	- 0.011
18	+ 0.008	39	- 0.012
19	+ 0.008	40	- 0.013
20	+ 0.007		

Baudin 6165

Temp.	Corr.
0	0.
1	- 0.0005
2	- 0.001
3	- 0.002
4	- 0.002
5	- 0.003
6	- 0.003
7	- 0.004
8	- 0.005
9	- 0.005
10	- 0.006
11	- 0.007
12	- 0.007
13	- 0.008
14	- 0.009
15	- 0.010
16	- 0.011
17	- 0.012
18	- 0.013
19	- 0.015
20	- 0.017
21	- 0.020
22	- 0.023
23	- 0.027
24	- 0.031
25	- 0.034
26	- 0.038
27	-.042
28	-.045
29	-.049
30	-.053

TABLE 12, concluded.

Baudin 6166.

Temp.	Corr.	Temp.	Corr.
0	+ 0.	16	+ 0.021
1	+ 0.001	17	+ 0.023
2	+ 0.003	18	+ 0.024
3	+ 0.004	19	+ 0.025
4	+ 0.005	20	+ 0.025
5	+ 0.006	21	+ 0.024
6	+ 0.008	22	+ 0.023
7	+ 0.009	23	+ 0.022
8	+ 0.011	24	+ 0.021
9	+ 0.012	25	+ 0.019
10	+ 0.013	26	+ 0.018
11	+ 0.015	27	+ 0.017
12	+ 0.016	28	+ 0.016
13	+ 0.017	29	+ 0.013
14	+ 0.018	30	+ 0.013
15	+ 0.020		

TABLE 13.

Simultaneous comparison of Rowland's Baudin thermometers, Nos. 6163, 6165, 6166.

(See Table 10 for abbreviations).

	6163	6165	6166
A.	770 mm.	770mm.	770 mm.
B.	104 mm.	35 mm.	68 mm.
C.	6.020	3.826	2.416
D.	6.016	3.820	2.410
A.	767 mm.	767 mm.	767 mm.
E.	10.587	9.524	
F.	10.341	9.152	
G.	5.083	5.089	
E.		9.741	9.222
F.		9.368	8.796
G.		5.280	5.278
E.	10.832		9.329
F.	10.586		8.903
G.	5.363		5.361
E.	14.783		15.031
F.	14.526		14.580
G.	9.780		9.774
E.	18.348	19.622	
F.	18.082	19.213	
G.	13.764	13.779	

A = barometer.
B = depth of ice
C = observed zero.
D = corrected zero.
E = observed reading.
F = corrected reading.
G = absolute scale.

TABLE 13, continued.

	6163	6165	6166
E.		19.650	20.208
F.		19.241	19.734
G.		13.803	13.779
E.	18.419		20.282
F.	18.153		19.808
G.	13.843		13.836
E.	22.541	25.109	
F.	22.264	24.680	
G.	18.420	18.346	
E.		25.118	26.221
F.		24.639	25.721
G.		18.444	18.405
E.	22.555		26.234
F.	22.278		25.734
G.	18.436		18.415
E.	30.937	36.365	
F.	30.638	35.894	
G.	27.655	27.697	
E.	31.007		38.215
F.	30.708		37.664
G.	27.733		27.712
E.		36.989	38.748
F.		36.516	38.195
G.		28.196	28.129

TABLE 14.

Results of the comparisons of the Baudin thermometers, collected from Table 13.

Baudin 6163.	Baudin 6165.	Baudin 6166.
5.088	5.089	
	5.280	5.278
5.363		5.361
9.730		9.774
13.764	13.779	
	13.803	13.779
13.843		13.836
18.420	18.436	
	18.444	18.405
18.436		18.415
27.655	27.697	
	28.196	28.129
27.773		27.712

From these comparisons, and from the correction curve for Baudin 6163, the following ordinates of the correction curves for B.6165 and 6166, have been deduced, calling H the temperature on the hydrogen scale, and B on the Baudin.

At 5°.2 $H = B_3 + 5 = B_5 + 4 = B_6 + 7$
At 9°.7 $H = B_3 + 8 = \quad = B_6 + 14$
At 13°.8 $H = B_3 + 9 = B_5 - 6 = B_6 + 16$
At 18°.4 $H = B_3 + 8 = B_5 - 8 = B_6 + 29$
At 27.8 $H = B_3 - 1 = B_5 - 43 = B_6 + 20$

Units are 0°.001

Curves on p, 47

TABLE 15.

Rowland's individual experiments on the Mechanical Equivalent, classified according to thermometer used. From p. 192, Rowland, Proc. Am. Acad., 15. 75, 1877 - 78.

Explanation, p. 3

Baudin 6163.

	Ja. 16.	Mch. 7	1st Mch. 24.	2nd Mch 24	May. 27.	June. 19.	Dec. 17	Dec. 19	Mean
7°				428.7			429.6	429.2	429.2
8				428.2			429.3	429.1	428.9
9				427.7			429.0	428.8	428.5
10				427.6			428.7	428.6	428.3
11				427.7			428.1	428.6	428.1
12				427.7			427.6	428.1	427.8
13			427.5	427.4			427.7	427.9	427.6
14			427.4	427.0			427.4	427.7	427.4
15	427.1		427.5	426.8			427.2	427.8	427.3
16	427.3		427.2	426.5			427.5	427.8	427.3
17	427.0		427.0	426.4			427.3	427.6	427.1
18	427.0	426.9	426.9	426.5			427.0	427.1	426.9
19	427.0	426.7	426.8	426.8			427.0	427.4	426.9
20	426.9	426.6	426.8	427.0			427.1	427.5	427.0
21	426.8	426.4	426.4	426.9	426.5				426.6
22		425.9		426.7	426.1				426.2
23		426.0		426.5	425.8				426.1
24		425.6			425.8				425.7
25		425.2			425.6				425.4
26		425.2			425.5	425.5			425.4
27		425.3			425.4	425.3			425.3
28		425.5			425.5	425.1			425.4
29		425.7			425.7	425.0			425.5
30		425.9			425.5	424.9			425.4
31		426.0			425.3	424.8			425.4
32		426.2			425.4	424.9			425.5
33					425.5	425.1			425.3
34					425.8	425.1			425.4
35					425.8	425.3			425.5
36					425.6	425.4			425.5

TABLE 15, continued.

	Baudin 6166.					Baudin 6165.
	May 15	Mch. 12	May 23.	Jun. 3.	Mean.	May 14.
14°	427.9				427.9	427.9
15	427.8				427.8	427.4
16	426.8				426.8	427.2
17	427.0				427.0	426.9
18	426.6				426.6	426.7
19	425.9				425.9	426.4
20	425.8	425.7			425.7	426.2
21	425.8	425.5			425.6	425.8
22	426.0	425.6	426.8		426.1	425.7
23	425.5	425.5	426.4	426.3	425.9	425.7
24	425.1	425.1	426.0	425.6	425.4	425.8
25	425.1	425.2	425.9	425.4	425.4	426.2
26	425.8	425.0	425.6	425.4	425.4	426.6
27	425.5				425.5	425.8
28						425.0

This table gives the mechanical equivalent of heat in kilogram-meters at Baltimore, each value calculated from a rise of 10° in temperature.

TABLE 16.

Calculation of the conversion factor, P, and of the product, JP, See p.34 for explanation.

Baudin 6163.

T	P - 1	J	JP = J′	T	P - 1	J	JP = J′
7°	- 0.0007	429.2	428.9	22	+ 0.0008	426.2	426.5
8	6	428.9	428.6	23	9	426.1	426.5
9	5	428.5	428.3	24	9	425.7	426.1
10	4	428.3	428.1	25	9	425.4	425.8
11	3	428.1	428.0	26	9	425.4	425.8
12	1	427.8	427.8	27	9	425.3	425.7
13	0	427.6	427.6	28	8	425.4	425.7
14	0	427.4	427.4	29	8	425.5	425.8
15	+ 0.0001	427.3	427.3	30	9	425.4	425.8
16	3	427.3	427.4	31	9	425.4	425.8
17	4	427.1	427.3	32	10	425.5	425.9
18	6	426.9	427.2	33	10	425.3	425.7
19	7	426.9	427.2	34	11	425.4	425.9
20	7	427.0	427.3	35	11	425.5	426.0
21	8	426.6	426.9	36	+ 0.0011#	425.5	426.0*

The first column headed T contains the temperature for which J is taken. The second column, headed P - 1, contains the conversion factor, P, diminished by 1, for convenience in calculation. The column headed J contains the values of the mechanical equivalent obtained from the means of Table 15. The column headed JP = J′, contains the value of J after applying the correction deduced from the correction curves for the Baudin thermometer, to reduce it to the Paris hydrogen scale.

TABLE 16, concluded.

	Baudin 6165			Baudin 6166.		
T	P - 1	J	JP = J'	P - 1	J	JP = J'
14	+ 0.0010	427.9	428.3	- 0.0013	427.9	427.3
15	11	427.4	427.9	12	427.8	427.3
16	13	427.2	427.8	9	426.8	426.4
17	16	426.9	427.6	7	427.0	426.7
18	19	426.7	427.5	5	426.6	426.4
19	22	426.4	427.3	3	425.9	425.8
20	24	427.2	427.2	+ 0.0001	425.7	425.7
21	27	425.8	426.9	3	425.6	425.7
22	30	425.7	427.0	6	426.1	426.4
23	32	425.7	427.1	8	425.9	426.2
24	34	425.8	427.2	11	425.4	425.9
25	36	426.2	427.7	12	425.4	425.9
26	37#	426.6	428.2	12#	425.4	425.9#
27	37#	425.8	427.4	13#	425.5	426.1#
28	37#	425.0	426.6			

Extrapolated.

TABLE 17.

Final Result.

A	B	C	D	E	A	B	C	D	E
5°				4212	21°	426.8	426.6	4181	4177
6		429.0	4204	4209	22	426.5	426.5	4180	4176
7	428.9	428.8	4202	4207	23	426.4	426.4	4179	4175
8	428.6	428.6	4200	4204	24	426.1	426.3	4178	4174
9	428.3	428.4	4199	4202	25	426.1	426.2	4177	4173
10	428.1	428.2	4197	4200	26	426.1	426.1	4176	4172
11	428.0	428.0	4195	4198	27	426.1	426.0	4175	4171
12	427.8	427.9	4194	4196	28	425.9	425.9	4174	4171
13	427.6	427.7	4192	4194	29	425.8	425.8	4173	4170
14	427.5	427.6	4191	4192	30	425.8	425.8	4173	4171
15	427.4	427.4	4189	4189	31	425.8	425.8	4173	4171
16	427.3	427.3	4188	4187	32	425.9	425.8	4173	4171
17	427.3	427.2	4187	4185	33	425.7	425.9	4174	4172
18	427.1	427.0	4185	4183	34	425.9	425.9	4174	4172
19	427.0	426.9	4184	4181	35	426.0	425.9	4174	4173
20	426.9	426.8	4183	4179	36	426.0	426.0	4175	4173

In the table above, column A is the absolute temperature. Column B is the mean of the corrected values for the mechanical equivalent in kilogram-meters at Baltimore, calculated from Table 16, giving to each value that was added in to form the mean, a weight equal to the number of experiments giving values at that temperature. Column C **has** the values obtained from a smooth curve. Column D is the same, reduced to the C.G.S. system. The numbers should be multiplied by 10^4. Column E has the uncorrected values on the C.G.S. system. These results are shown in the curves on p.48 and p.49.

Table 18.

Calibration corrections for Tonnelot thermometers

Tonnelot 11800

[illegible] Correction

-2	0.0000	[illegible]4	-0.04[illegible]4	[illegible]	-0.0412	[illegible]	-0.0[illegible]5
0	+0.01[illegible]	[illegible]6	-0.0440	[illegible]	-0.0394	[illegible]	-0.0329
[illegible]	+0.0[illegible]8	28	-0.0410	[illegible]	0.0411	[illegible]	-0.02[illegible]3
4	+0.0250	[illegible]	-0.04[illegible]	[illegible]	0.036[illegible]	[illegible]	-0.01[illegible]2
6	+0.0070	[illegible]	-0.0482	[illegible]	-0.0276	[illegible]4	+0.0106
8	-0.0084	[illegible]	-0.0531	[illegible]	-0.0314	[illegible]	+0.0239
[illegible]	-0.0289	[illegible]	0.0610	[illegible]	-0.0455		+0.0366
12	-0.0226	[illegible]	-0.0607	[illegible]	-0.0557		+0.0378
[illegible]4	-0.0170	[illegible]4	-0.0608	[illegible]	0.0626	[illegible]	+0.0228
	-0.0205	4[illegible]	-0.0556	68	-0.0625	[illegible]	+0.0040
[illegible]	-0.0317	[illegible]4	-0.0459	[illegible]	-0.0645	[illegible]	-0.0022
2[illegible]	-0.03[illegible]2	4[illegible]	-0.0410	[illegible]	-0.0539	98	0.0000
[illegible]	-0.0404	4[illegible]	-0.0416	[illegible]	-0.04[illegible]		

Tonnelot 11801

-4	~~+0.0167~~	24	+0.0041	[illegible]	+0.0392	8[illegible]	+0.0[illegible]33
-2	+0.0169	2[illegible]	+0.0043	[illegible]	+0.0502	[illegible]2	+[illegible]611
0	0.0000	2[illegible]	+0.0129	[illegible]	+0.0[illegible]38	84	+0.04[illegible]2
+2	-0.01[illegible]4	[illegible]	+0.0109	[illegible]	+0.0[illegible]96	[illegible]	+0.0[illegible]23
4	-0.0278	[illegible]	+0.0123	6[illegible]	+0.0636		+0.0244
6	-0.0261	[illegible]	+0.0020	[illegible]	+0.06[illegible]1	[illegible]	+0.0166
[illegible]	-0.0219	[illegible]	-0.0171	6[illegible]	+0.0720	[illegible]	+0.0108
[illegible]	-0.00[illegible]2	[illegible]	-0.0437	[illegible]6	+0.0800	[illegible]4	+0.0044
[illegible]	-0.0022	4	0.0479	6[illegible]	+0.0809	[illegible]6	-0.0023
14	+0.0067	[illegible]2	-0.0477	7[illegible]	+0.0794	[illegible]	-0.0013
1[illegible]	+0.0[illegible]77	4[illegible]	-0.0324	7[illegible]	+0.0813	10[illegible]	0.0000
1[illegible]	+0.0[illegible]6	4[illegible]	-0.0102	[illegible]4	0.0802	102	+0.0188
[illegible]	+0.0[illegible]44	4[illegible]	+0.0126	[illegible]6	+0.0722		
[illegible]	+0.0[illegible]33	[illegible]0	+0.02[illegible]	7[illegible]	+[illegible]922		

Table 18, concluded.

Calibration corrections.

Tonnelot 11811

−2	−0.0318	14	+0.0655	30	−0.0003	46	+0.0162
0	0.0000	16	+0.0527	32	+0.0072	48	+0.00[illegible]2
+2	+0.0238	18	+0.0409	34	+0.0121	50	−0.0024
4	+0.0488	20	+0.0283	36	+0.0255	52	−0.019[illegible]
6	+0.0674	22	+0.0224	38	+0.0319		.. ..
8	+0.0784	24	+0.0145	40	+0.0414	98	+0.0168
10	+0.07[illegible]2	26	+0.0111	42	+0.0333	100	0.0000
12	+0.0698	28	−0.0094	44	+0.0218	102	−0.0261

Table 19.

Example of a comparison, giving all the original data recorded at the time, together with the complete reduction. The example taken is the comparison between Tonnelot 11801 and Baudin 6165, made on the 24th March, 1897. This particular case was selected at random on account of the fact that, on the curve, there seemed to be a little irregularity.

Thermometer Baudin 6165 put in ice at 10:10 A.M. At 1 P.M. the barometer read 74.04 cm. An aneroid barometer was used to measure the atmospheric pressure, and it was compared at least once every day with a mercury barometer, except in one or two cases.

Micrometer readings of the zero point of Baudin 6165.

Setting.	Readings.		
3.8 cm.	16.920 mm.	16.920 mm	16.925 mm
Dif.	.23	.229	.231 mm.
Thread.	16.69 mm.	16.691 mm.	16.694
Dif.	.935	.99	.99
3.9 cm.	15.935	15.93 mm.	15.935 mm.
Time of obs.	2 h. 43 min.		3 h. 28 min. P.M.

Table 19, continued.

Comparison in the tank.

Tonnelot 11801

	I.	III.
10°.3	12.315 mm.	8.430 mm.
	.455	.45
Thread.	11.860	7.980 mm.
	.595	.60
10°.4	11.720	7.83
Time	3:54 P.M.	3h. 58 m.

Baudin 6165.

	II.
15.5 cm.	10.412 mm.
Dif.	.102
Thread.	10.31
Dif.	1.002
15.6 cm.	9.410
Time.	- - - -

Water stirred up.

Baudin 6165.

	I.	III.
15.6 cm.	13.398 mm.	10.726 mm.
	.623	.626
Thread.	12.775 mm.	10.10
	.998	1.006 mm.
15.7 cm	12.40	9.72 mm.
Time	4:13 P.M.	4:17 P.M.

Table 19, continued.

Tonnelot 11801.

	II.	IV.
10°.5	11.585 mm.	8.275 mm.
Dif.	.035	.047
Thread.	11.55 mm.	8.228 mm.
Dif.	.595	.535
10°.6	11.99 mm.	7.69 mm.
Time	------	-------

Zero of Tonnelot 11801

0°	8.628 mm.	8.622 mm.	8.625 mm
Dif.	.168	.180	.168
Thread.	8.46	8.442	8.457
Dif.	.660	.622	.627
+ 0°.1	7.998mm.	8.000mm.	7.998mm.
		4h. 46 m.P.M.	4 h. 43 m.

In taking zero points, unless otherwise mentioned, the water in the zero tank was as high as the point on the thermometer where the zero actually was.

This example here shows that on the thermometer Tonnelot 11801, the mark + 0°.1 was too high. It is displaced by about 0.04 mm. which is about 7%. This however did not have any effect on the readings, as the average value of a degree was used in reducing the micrometer readings. For this thermometer it was 5.858 mm.

Table 19, continued.

Reduction of readings. Tonnelot 11301.

	Temperature measured.	Corres. zero
Barometer	740 mm.	740 mm.
Water in tank 57 mm. = Hg.	4 mm	
Water in zero tank. 59 mm. = Hg.		4 mm.
Total pressures.	744 mm.	744 mm.

Readings.	10°.377	
	10°.507	
Mean of the two	10°.442	+ 0.029
Calibration correction	- 0..008	0
Interior pressure	------	+ 0.008
Exterior pressure.	+ 0°.002	+ 0.002
Zero.	- 0°.039	+ 0.039
	10°.397	
Fundamental-interval.	0	
Correction to mean of hard glass thermometers	- 0°.005	
Correction to hydrogen sc.	- 0°.054	
Temp. on hydrogen scale.	10°.338	

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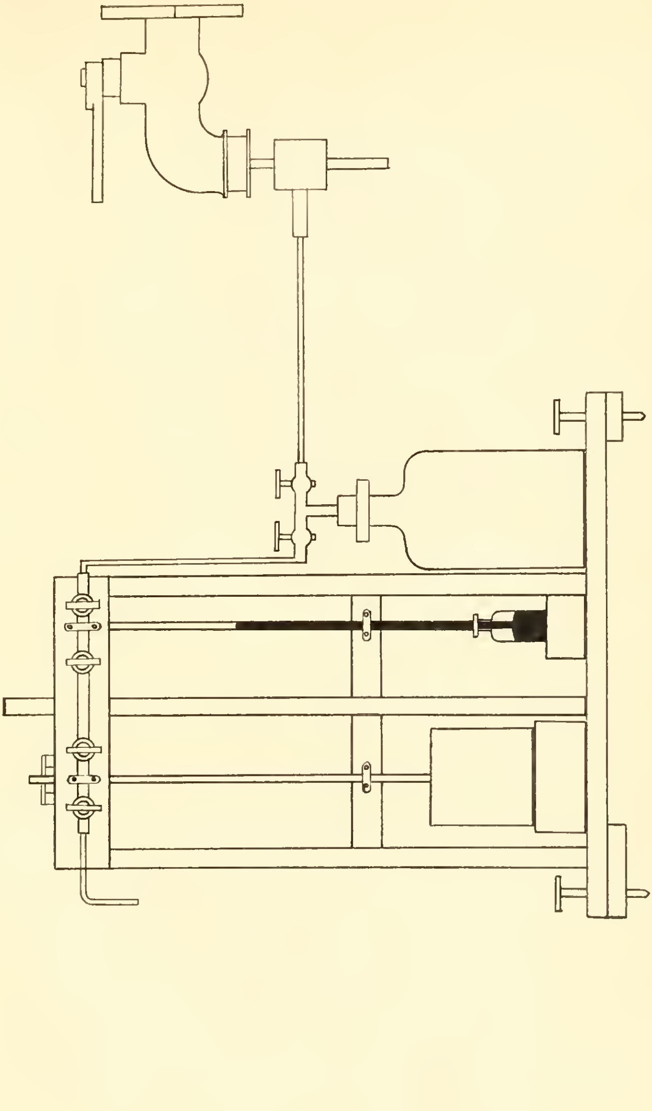
Baudin 6165.

Barometer	740 mm.
Ice 75 mm =	5
Pressure in ice.	745 mm.
Reading in ice.	3.823 cm.
Exterior pressure	+0.005
Corrected zero	3.828 cm.
Rowland's table	3.5
Zero correction.	- 0.328 cm.

Readings	15.510 cm
	15.662
Mean value	15.586
Exterior pressure	+ .005
Int. pr. 193 mm × β	-0 070
Zero	0.323
	15.193 cm.
Absolute scale	10°.343

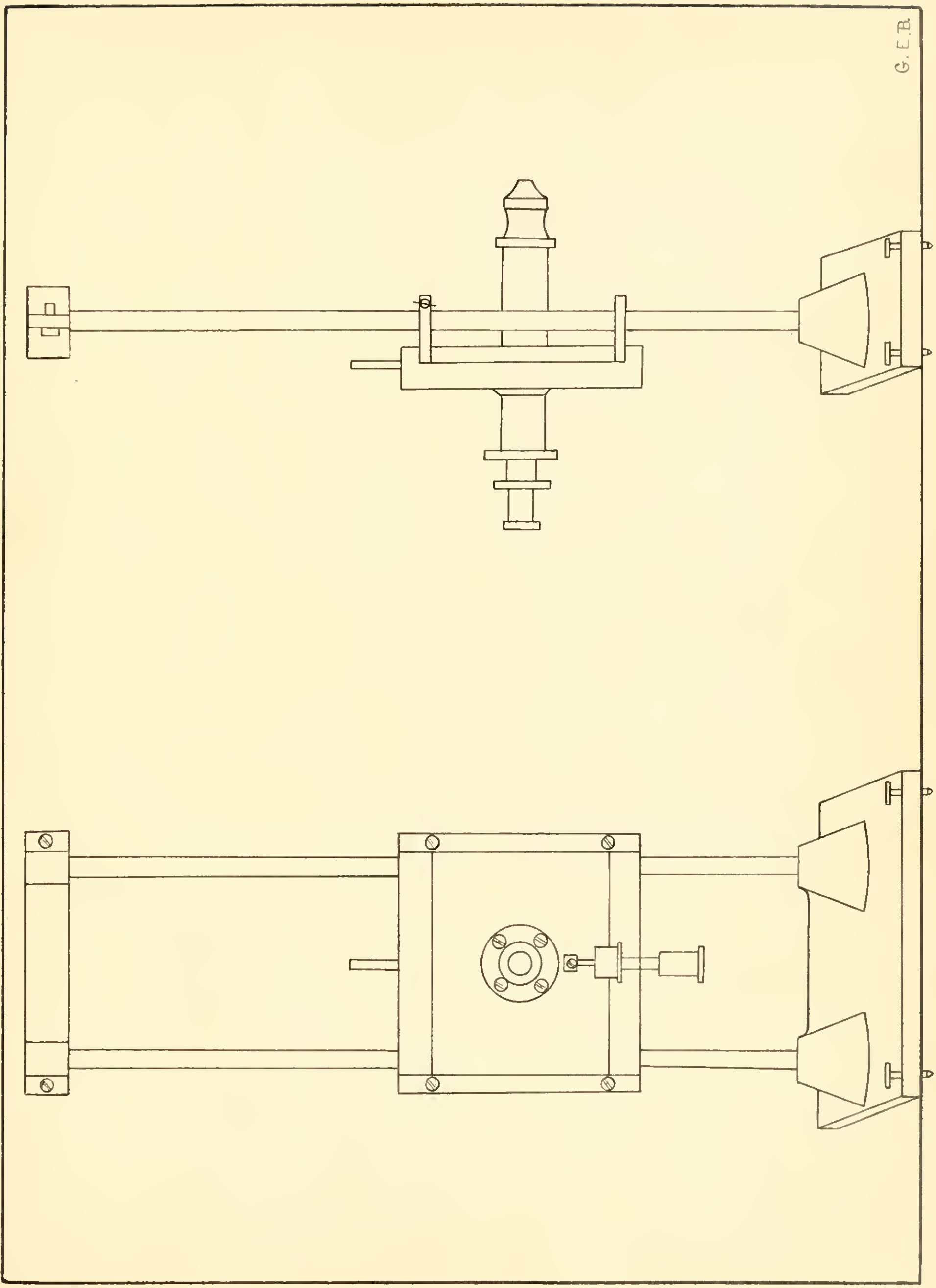
Fig. 1.



G. E. B.

Diagrammatic Drawings.

Fig. 2.



Diagrammatic Drawings.

Fig. 3.

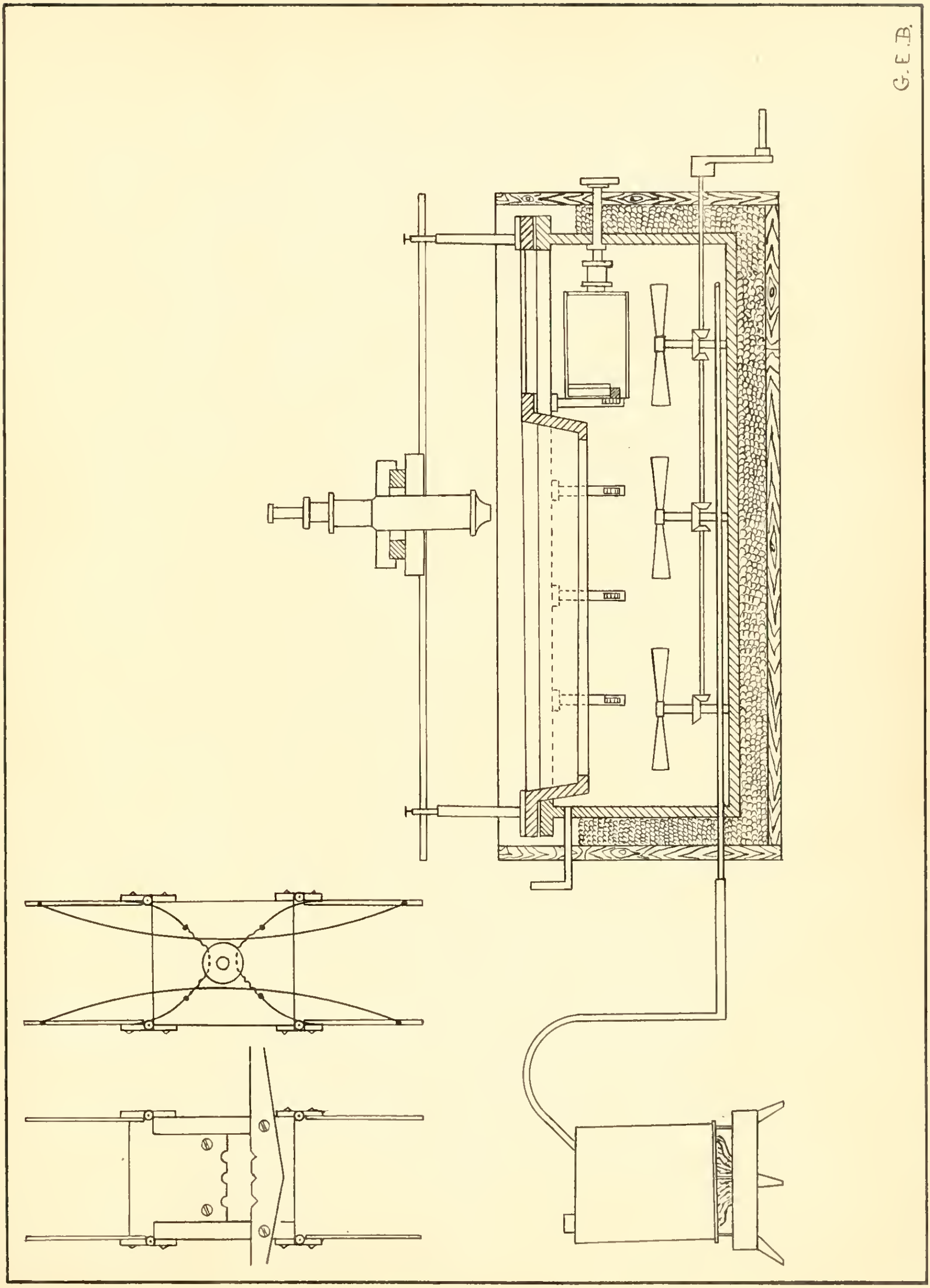
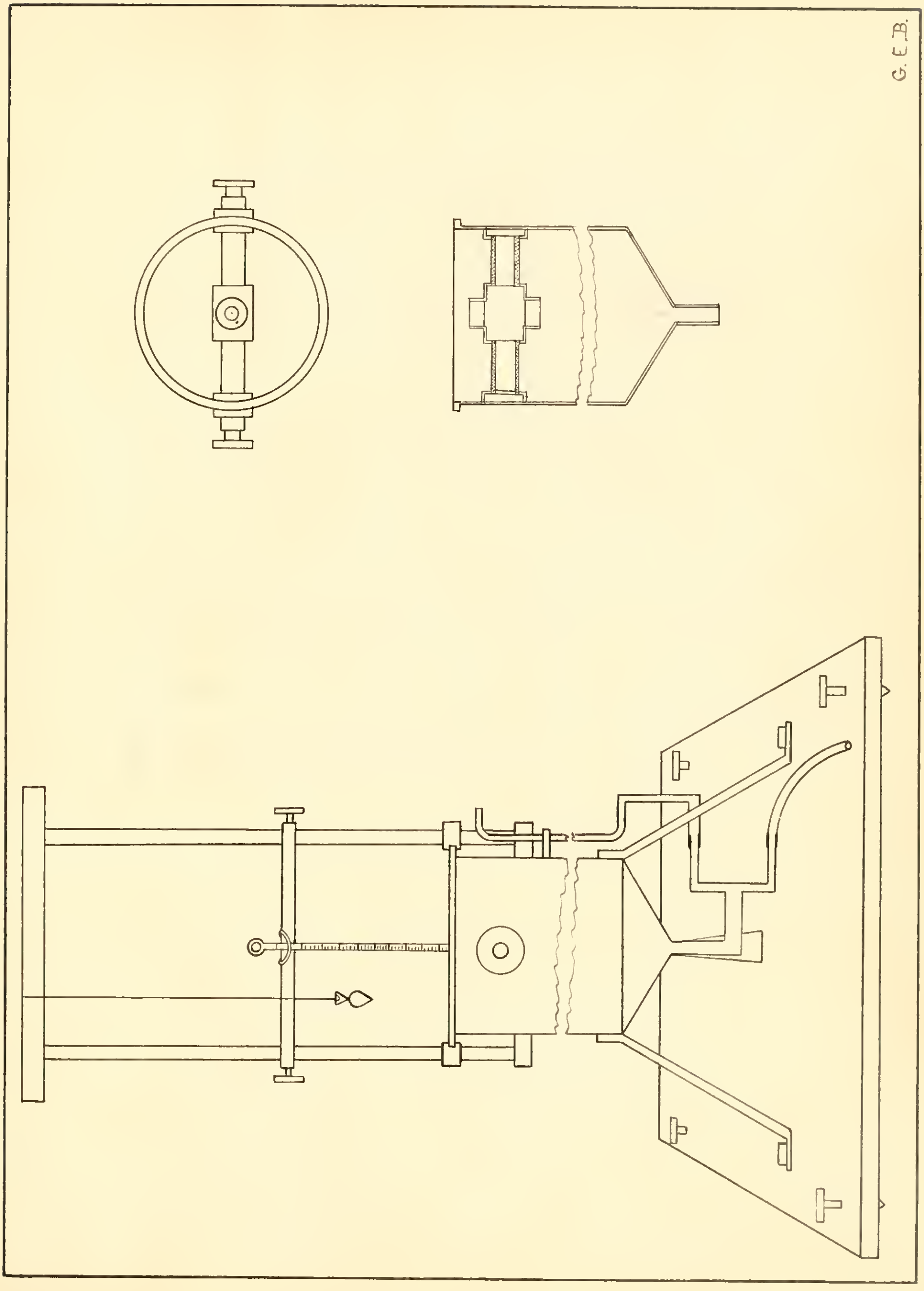


Fig. 4.



The author was born in New York City on the 2nd of January, 1864. He was educated in private schools in that city, and in October, 1880, he entered the academic department of Columbia College. He graduated in June, 1884, receiving the degree of A.B. He then entered business life in which he remained until 1891. In October of that year he entered the Johns Hopkins University as a graduate student in Physics. In 1895-96, he was appointed a student-assistant in the Physical Laboratory of the Johns Hopkins University.